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GEOPHYSICS

A Journal of General and Applied Geophysics

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Society of Exploration Geophysicists

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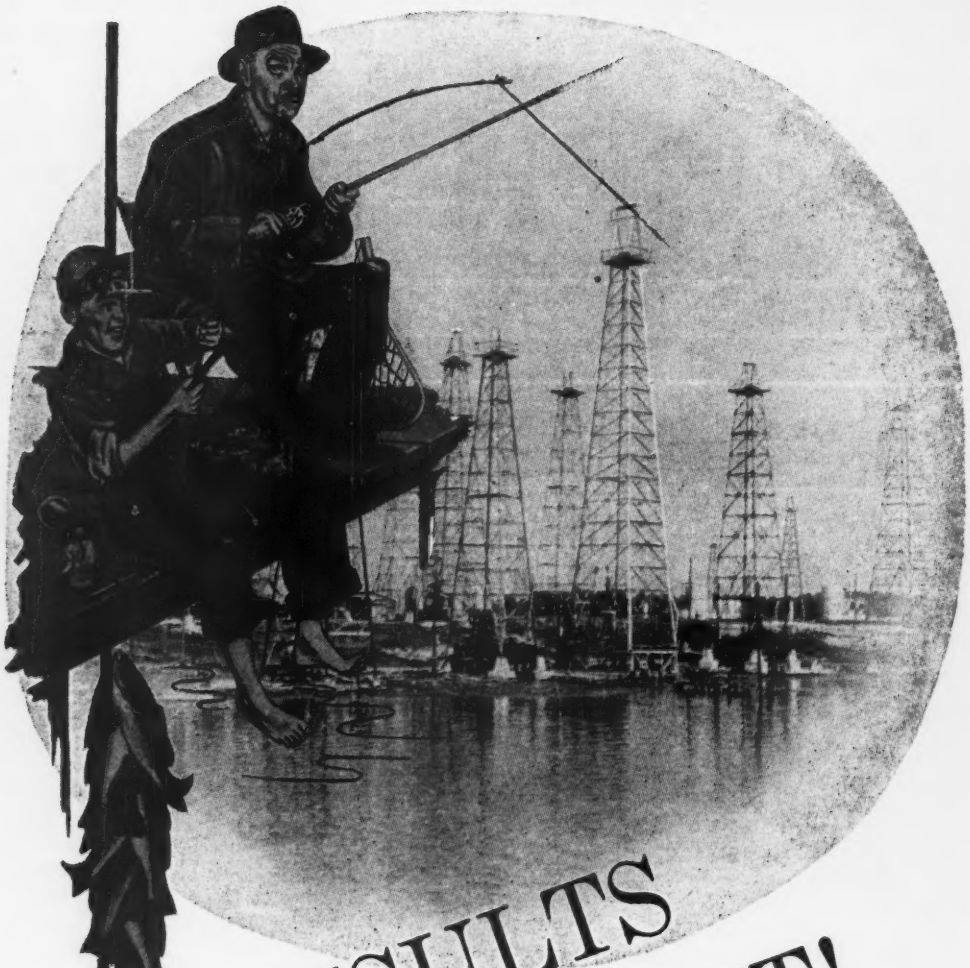

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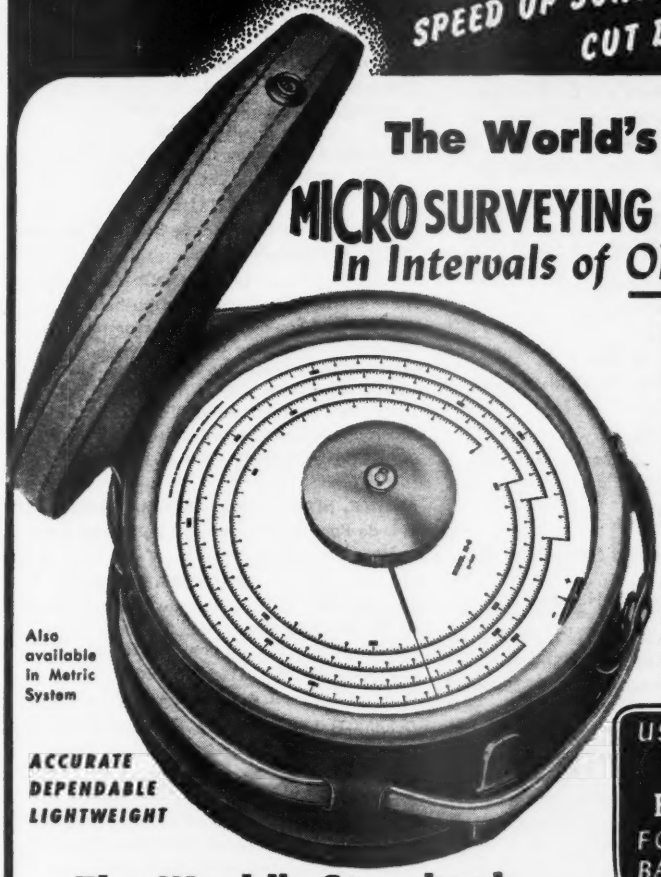

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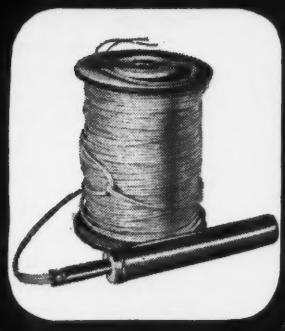

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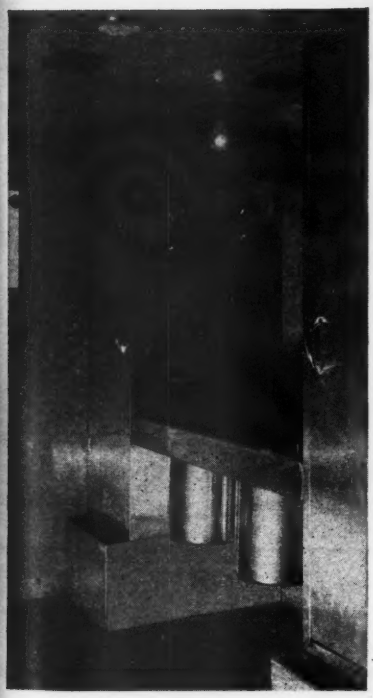

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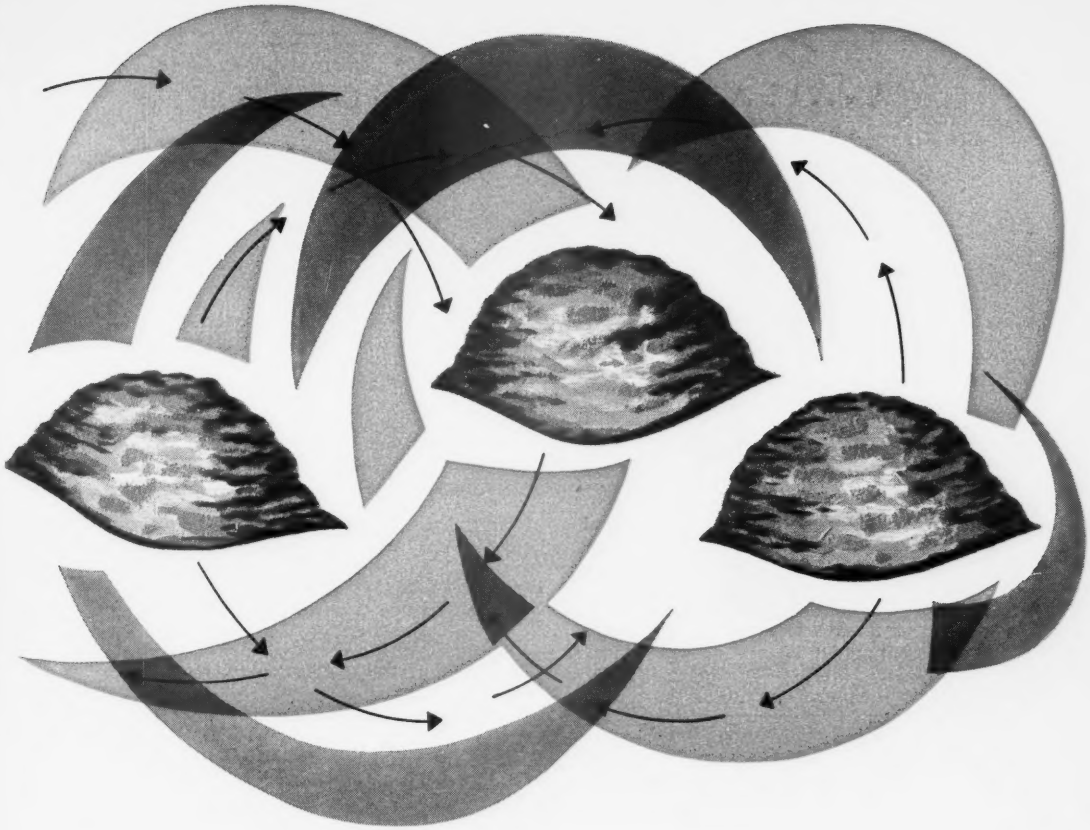

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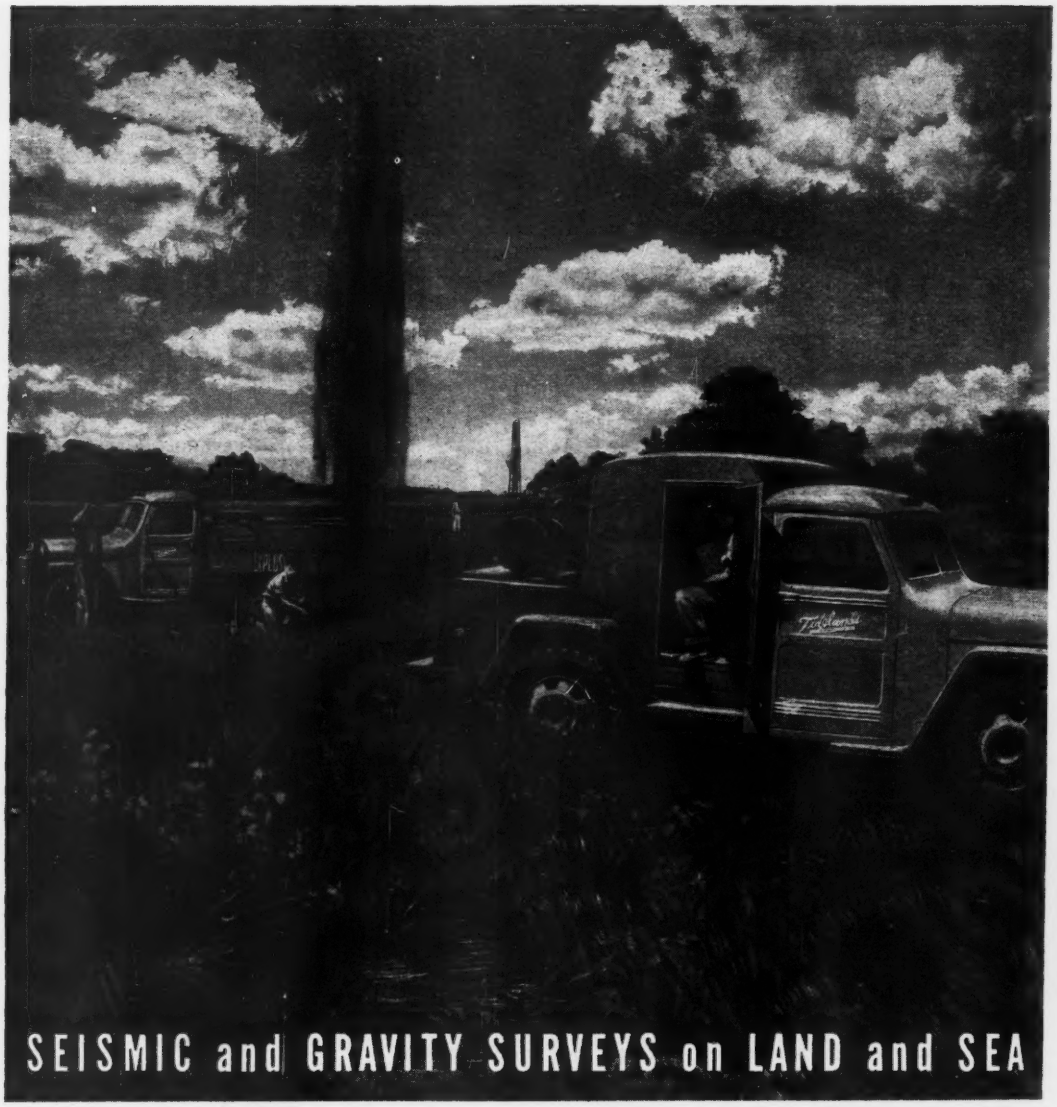

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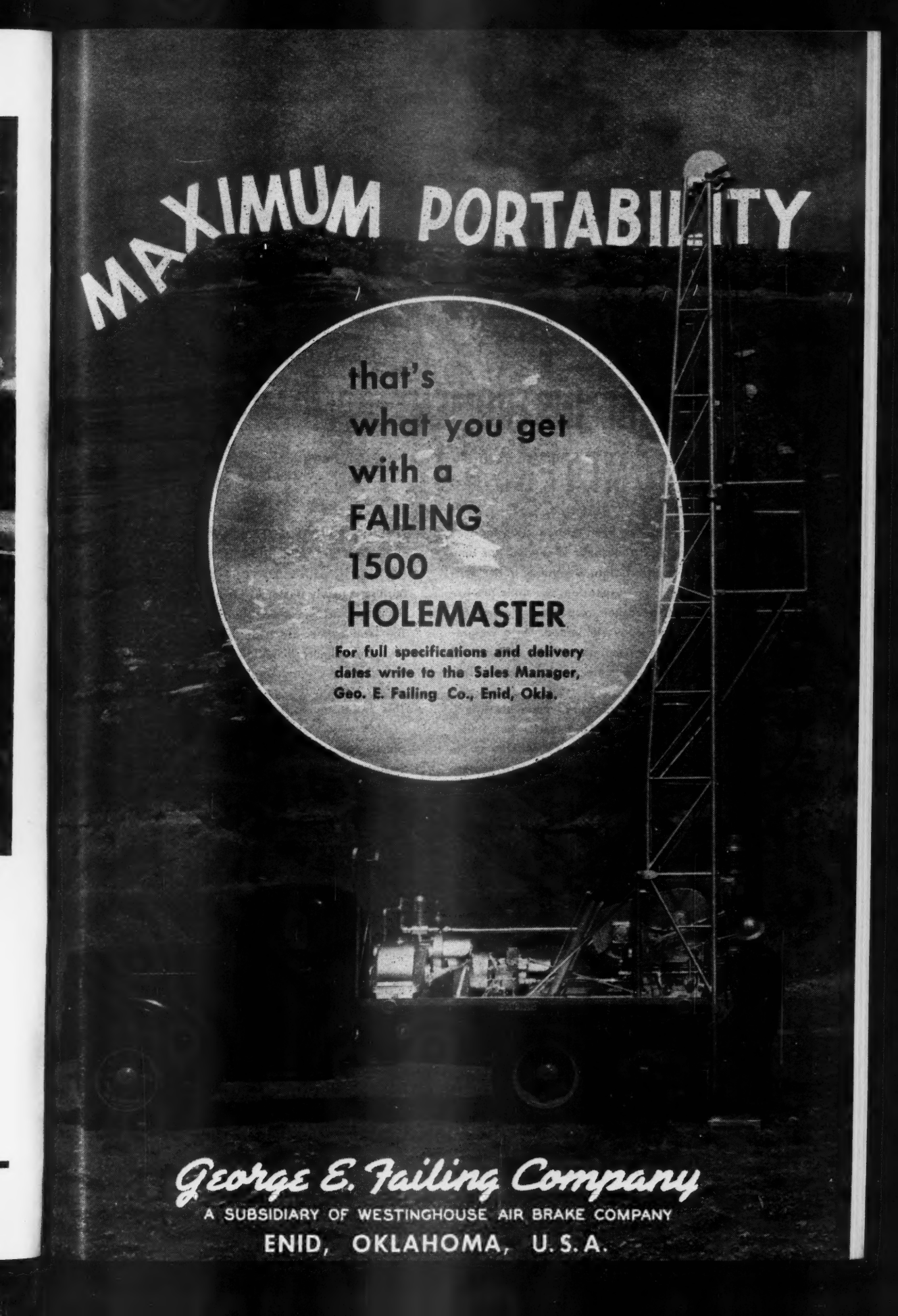
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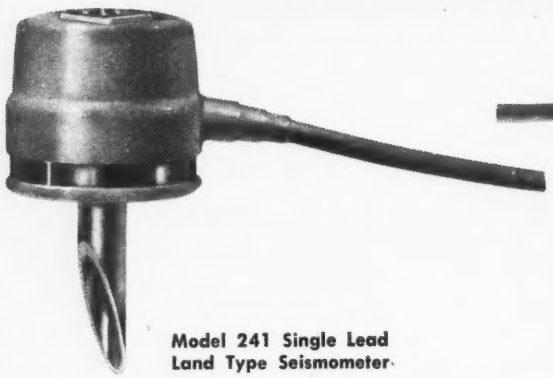

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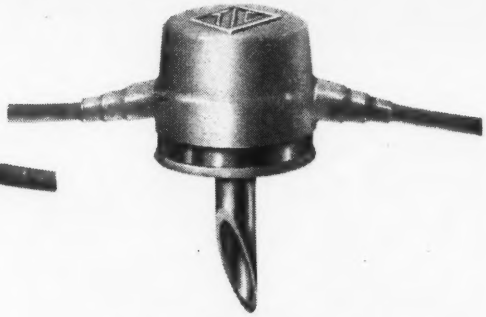

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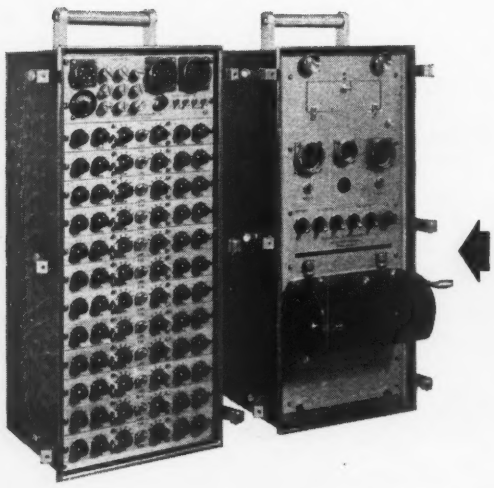

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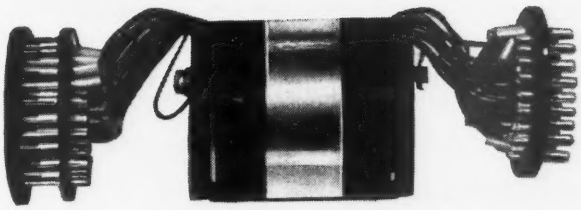

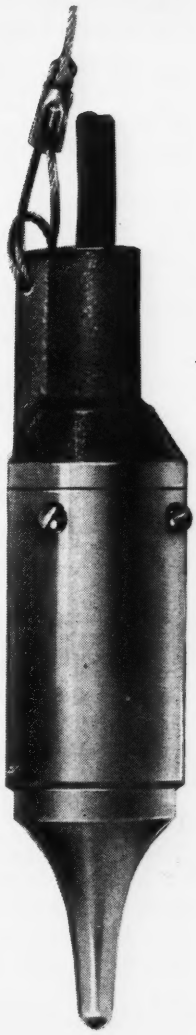

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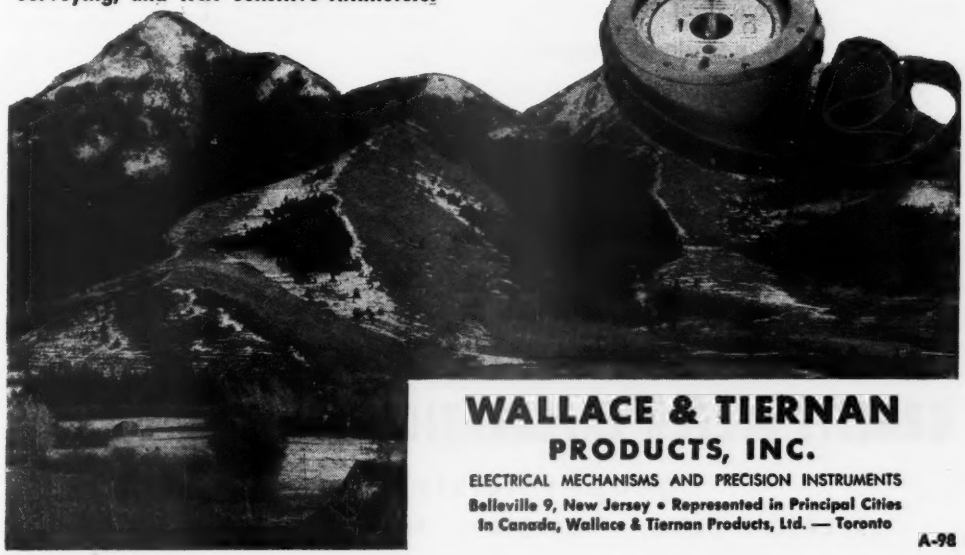

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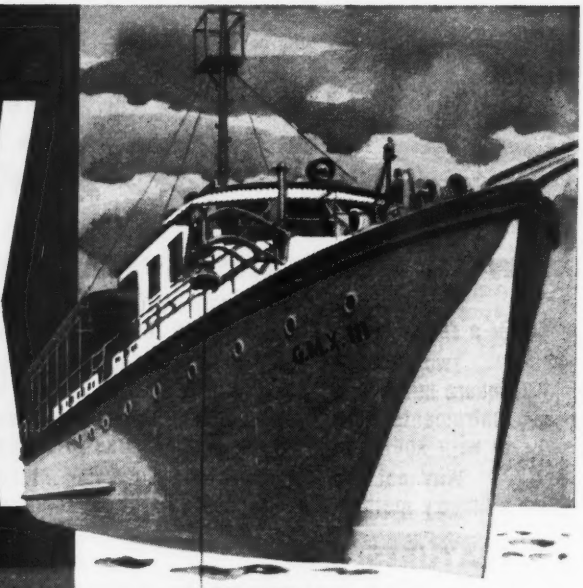

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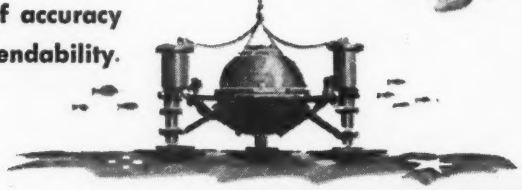

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WAVELET CONTRACTION, WAVELET EXPANSION, AND THE CONTROL OF SEISMIC RESOLUTION*

NORMAN RICKER†

ABSTRACT

The general problem of seismic resolution is discussed. A seismogram, free from distortions, is an elaborate *wavelet complex*, and the analysis of a seismogram consists in breaking it down into its wavelet components. Distortions introduced by conventional seismographs are discussed and the conditions to be imposed upon seismic apparatus for distortionless wavelet transmission are set down. Three distortionless systems are possible: flat response; the wavelet contractor; and the wavelet expander. Wavelet contraction is discussed, whereby the individual wavelets which go to make up the seismogram may be contracted to a lesser breadth without altering the relative arrival times of the wavelet centers. Laboratory studies of the wavelet contractor are described and examples of wavelet contraction and the resolution of wavelet complexes are given. A description of the wavelet contracting seismograph used in the evaluation of the device in the field is given and results of the evaluation program are discussed. The wavelet contractor delineates subsurface formations with greater precision than does the conventional seismograph and it is able to carry pinchouts and truncations farther than is possible with conventional seismographs.

WAVELET COMPLEXES AND SEISMIC RESOLUTION

For some time now, we have been giving considerable attention to the form of the seismic disturbance which proceeds outward from the explosion of a charge of dynamite at a point in the earth; and the experimental studies (Ricker, 1953), resulting from this investigation, have shown that we now have a fairly clear understanding of the form and laws of propagation of the disturbance. These experimental studies have been made in an earth as nearly homogeneous and isotropic as could readily be found.

Why is it so important to know the nature of the disturbance in a homogeneous and isotropic earth when actually we know the earth in general to be of a much more complicated nature? We shall endeavor to show how the studies made in a homogeneous and isotropic earth may be extended into an actual layered earth. Considering now an actual layered earth, let us suppose that we fire a

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† Senior Research Physicist, Research Laboratories, The Carter Oil Company, Tulsa, Oklahoma.

charge of dynamite, in the customary manner, at a point just below the surface of the earth. As the primary disturbance moves downward it strikes in succession the series of reflecting beds, and at each interface a disturbance is returned, of form identical with the primary form, provided the incidence is normal.

If the interfaces are not too closely spaced, the disturbances arriving at the surface of the ground and detected by the geophones will be a series of well spaced wavelet forms. If, however, the interfaces are closely spaced, these wavelets, because of their finite breadths, will tend to overlap, and, instead of a simple seismogram, there will result a complicated seismogram which may be very difficult to interpret.

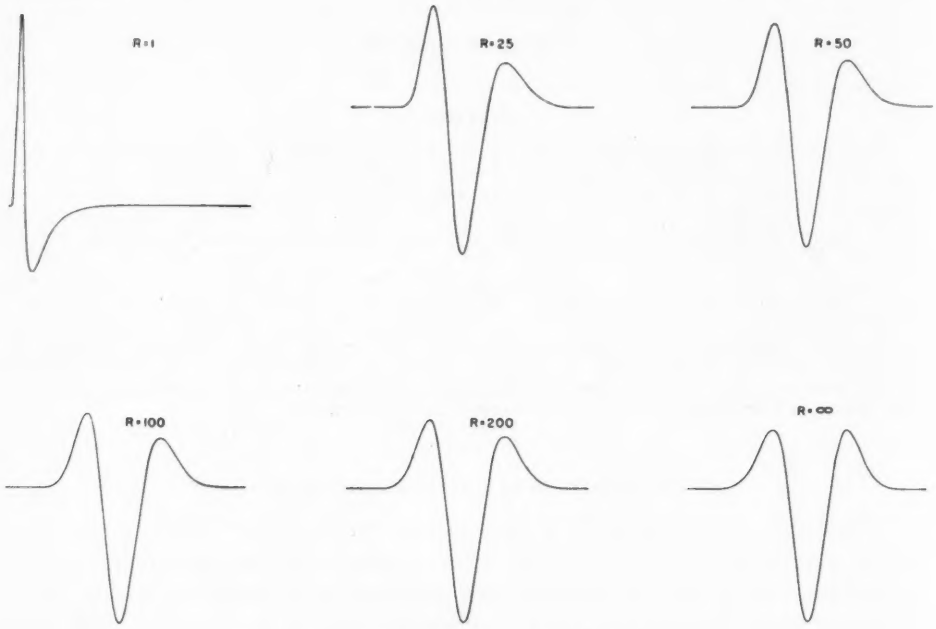

FIG. 1. The velocity type wavelet forms $\mathcal{V}(u|R)$.

We shall, for the moment, assume that no distortion is introduced by the seismic apparatus, and that the seismograph records faithfully the true motion of the earth, except, of course, for the elimination of low frequency surface waves.

A disturbance formed by two or more overlapping wavelets we shall call a *wavelet complex*, and our seismogram, of course, is a very elaborate wavelet complex. On Figure 1 we show several variations of the velocity-type seismic wavelet. These forms have been shown before. Any of them may be used in the construction of wavelet complexes, but for the present discussion it shall be sufficient to consider only the symmetrical form, $\mathcal{V}(u|\infty)$, shown in the lower right hand corner of the figure.

We shall now build up some simple wavelet complexes. On Figure 2 there are

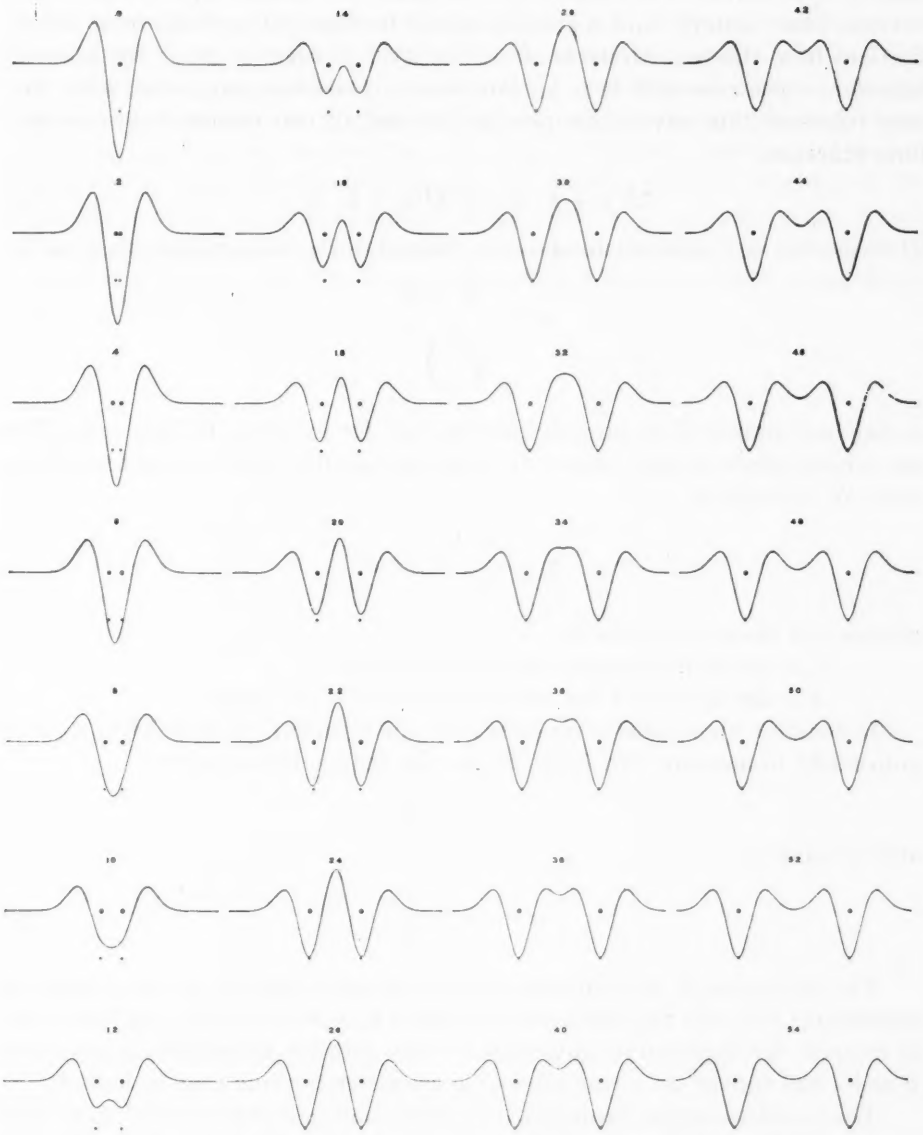

FIG. 2. The two-wavelet complex $\mathcal{V}(u+\delta|\infty)+\mathcal{V}(u-\delta|\infty)$.

shown a series of wavelet complexes, each consisting of two erect, symmetrical, velocity-type wavelets, of equal amplitudes, and with various separations in time between their centers. Such a complex would be expected to result from the reflections from the two interfaces of a three-layer problem in which the acoustic impedance increases each time an interface is crossed in going downward. We may represent this wavelet complex by the sum of two velocity-type wavelet-form functions

$$\mathcal{V}(u + \delta \mid \infty) + \mathcal{V}(u - \delta \mid \infty). \tag{1}$$

The variable, u, is dimensionless and is defined, for a homogeneous medium by

$$u = \frac{T - R}{\left(\frac{R}{2}\right)^{1/2}} \tag{2}$$

as has been indicated in previous papers (see, for example, Ricker, 1953.) For our present needs we must know u in terms of quantities which are measurable as time. We have then

$$u = \frac{2\sqrt{6}}{b}(t - t_0) \tag{3}$$

wherein t is the time in seconds

t_0 is the arrival time of the wavelet center

b is the breadth of the wavelet between its two peaks.

In building up wavelet-complexes from the symmetrical form $\mathcal{V}(u \mid \infty)$ it is convenient to measure time from the wavelet center. Hence we let

$$\tau = t - t_0 \tag{4}$$

and we have

$$u = 2\sqrt{6} \cdot \frac{\tau}{b} \cdot \tag{5}$$

The separation of the centers of the two wavelets making up the complex of expression (1) is 2δ in the dimensionless scale of u, or $b\delta/\sqrt{6}$ in the true time scale, in seconds. We shall find it convenient to work with the dimensionless quantities u and δ and convert to a true time scale whenever the true time is desired.

The wavelet-complex represented by expression (1) and shown on Figure 2 has been drawn for a number of values of the separation parameter, δ. With the value of δ set at 5.4 the two wavelets making up the complex are well separated and may be seen as distinct. In the sequence of forms of this wavelet-complex the centers of the two individual wavelet components are marked with small circles, and the positions of the central valleys of these individual wavelets are marked with small black dots. Starting with the larger values of δ we see that as the two

wavelets are moved closer together the first thing worthy of notice is the merging of the inner maxima which occurs between $\delta = 3.4$ and $\delta = 3.2$. The central valleys still, however, have approximately their full depths, and picks made on these valleys are representative of the positions of the wavelet centers. The next thing that happens is the weakening of the depth of the valleys which begins to become noticeable at around $\delta = 2.4$. Also there is a very slight error in pick. At $\delta = 1.6$ the error in pick may be troublesome, the distance between wavelet centers being actually less than the distance between the valleys which we would pick. As δ becomes still less we see that at some point between $\delta = 1.2$ and $\delta = 1.0$, the complex is no longer resolved. The point of resolution then occurs somewhere between these values of δ. In Figure 3 this interval has been more closely divided

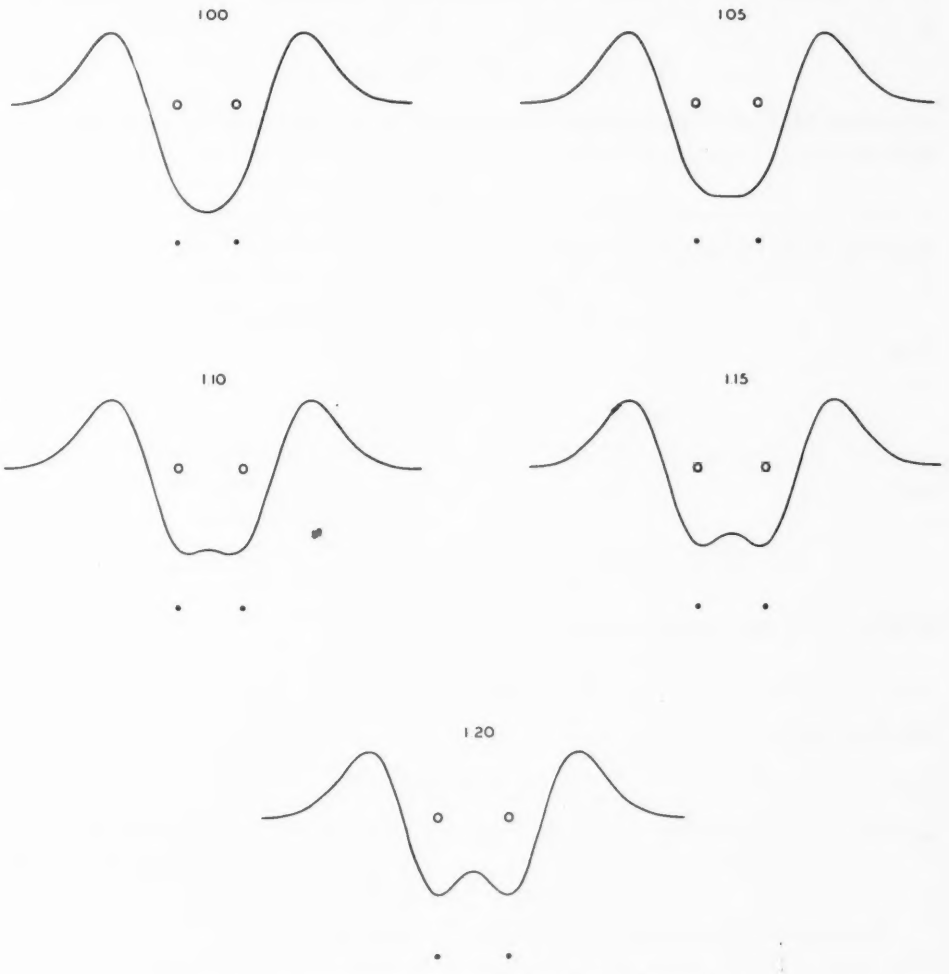

FIG. 3. The two-wavelet complex $\mathfrak{V}(u+\delta|\infty)+\mathfrak{V}(u-\delta|\infty)$.

and we see that the point of resolution occurs somewhere between 1.10 and 1.00, probably lying close to $\delta = 1.05$.

We may calculate precisely the point of resolution in the following manner:

We note that at the onset of resolution the curvature of the form at $u=0$ changes sign. In other words, the curvature at that point is zero and hence the second derivative with respect to u must vanish. Hence

$$\frac{d^2}{du^2}\left[\mathcal{V}(u+\delta\,|\,\infty)+\mathcal{V}(u-\delta\,|\,\infty)\right]=0 \quad \text{at } u=0. \tag{6}$$

So we want

$$\mathcal{V}''(u+\delta\,|\,\infty)+\mathcal{V}''(u-\delta\,|\,\infty)=0 \quad \text{at } u=0 \tag{7}$$

or

$$\mathcal{V}''(\delta\,|\,\infty)+\mathcal{V}''(-\delta\,|\,\infty)=0. \tag{8}$$

Now since $\mathcal{V}(\delta\,|\,\infty)$ is an even function of δ, $\mathcal{V}''(\delta\,|\,\infty)$ will also be an even function of δ and so

$$\mathcal{V}''(-\delta\,|\,\infty)=\mathcal{V}''(\delta\,|\,\infty). \tag{9}$$

Thus we want the value of δ for which

$$\mathcal{V}''(\delta\,|\,\infty)=0. \tag{10}$$

Now

$$\mathcal{V}(\delta\,|\,\infty)\equiv\left(\frac{\delta^2}{4}-\frac{1}{2}\right)\frac{\sqrt{\pi}}{2}\cdot e^{-\delta^2/4} \tag{11}$$

and

$$\mathcal{V}''(\delta\,|\,\infty)\equiv\frac{1}{16}(\delta^4-12\delta^2+12)\frac{\sqrt{\pi}}{2}\cdot e^{-\delta^2/4} \tag{12}$$

so $\mathcal{V}''(\delta\,|\,\infty)$ will vanish at the roots of

$$\delta^4-12\delta^2+12=0. \tag{13}$$

We have then

$$\delta^2=6\pm 2\sqrt{6} \tag{14}$$

or

$$\delta=\pm(\sqrt{6}\pm 2\sqrt{6})^{1/2}. \tag{15}$$

Thus we obtain as approximate roots of equation (13)

$$\delta=\pm 1.0493 \quad \text{and} \quad \pm 3.3014. \tag{16}$$

The value 1.0493 gives the resolution point we have just been discussing. The other value, 3.3014, gives the resolution point, where the inner maxima merged between $\delta = 3.4$ and $\delta = 3.2$, discussed earlier. We have, since

$$2\delta = \text{distance between wavelet centers in the scale of } u$$

and

$$2\sqrt{6} = \text{wavelet breadth in scale of } u,$$

$$\frac{\delta}{\sqrt{6}} = \frac{\text{distance between wavelet centers}}{\text{wavelet breadth}}$$

in any scale, including the true time scale, and at the resolution point ($\delta = 1.0493$)

$$\frac{\delta}{\sqrt{6}} = .428. \tag{17}$$

Thus we see that the wavelet components of this wavelet complex are resolved only when the wavelet centers are separated in time by an amount greater than .428 of the wavelet breadth.

Thus for the first time we are able to obtain a precise figure for a problem in seismic resolution. If the above wavelet complex arises from the overlapping of the reflections from two reflecting interfaces and if c is the wavelet velocity in the bed lying between these two interfaces, we have

$$\Delta t = \frac{2\Delta h}{c} \tag{18}$$

wherein Δt is the time interval between the two reflections and Δh is the distance between the interfaces.

Now at the resolution point

$$\frac{\Delta t}{b} = .428 \tag{19}$$

so that

$$\Delta h = .428 \frac{bc}{2} \tag{20}$$

or

$$\Delta h = .214\, bc. \tag{21}$$

As an example, if the velocity is 10,000 feet per second and the wavelet breadth is .020 seconds, then

$$\Delta h = 42.8 \text{ feet.}$$

In this instance we shall not be able to map interfaces closer together than 42.8 feet.

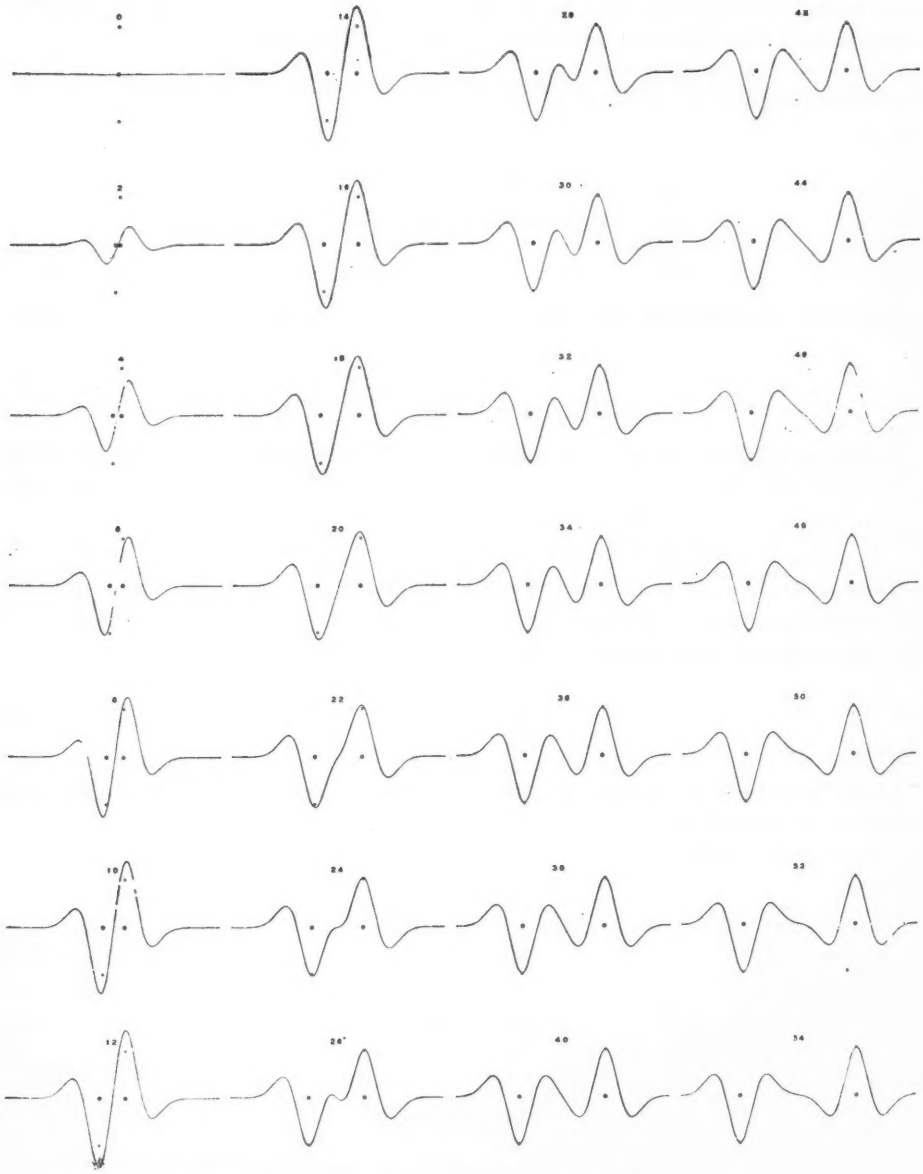

FIG. 4. The two-wavelet complex $\mathcal{V}(u+\delta|\infty)-\mathcal{V}(u-\delta|\infty)$.

In Figure 4 there is shown the wavelet complex

$$\mathfrak{V}(u + \delta \mid \infty) - \mathfrak{V}(u - \delta \mid \infty) \tag{22}$$

which is composed of two symmetrical, velocity-type wavelets of equal amplitudes, the first erect and the second inverted, and with their centers separated an amount 2δ in the scale of u. This is the type of complex one would expect from the reflections off the top and base of a single hard stratum imbedded in a softer material. For the larger values of δ the wavelets are fairly well separated and are resolved. As the two wavelets are moved closer and closer together we notice significant changes in the form of the complex until somewhere around the middle of the second column of wave forms the central wrinkle has disappeared. At this point the prominent valley and the prominent peak still have arrival times close to those of the wavelet centers. This continues to be the case for a few more forms as the centers are brought closer together.

Gradually, however, the valley and peak no longer move along with the wavelet centers and the only change in the form is then a loss in amplitude. A little thought will reveal the fact that the over-all form of the complex has now become the derivative of a single velocity-type wavelet form. As the reflecting bed then becomes thinner and thinner, this thinning cannot be followed by a coming together of peak and valley, but must be followed through a study of the *loss in amplitude.*

Mathematical studies to determine resolution points such as were made for the other complex may be carried out quite easily. However, these few examples of seismic resolution are given merely for the purpose of showing some of the interesting studies which may be made of the seismograms as long as the seismograph itself is free from distortions. With most seismographs which have been used in the past there is a very considerable distortion introduced by the instrument itself. This is illustrated by Figure 5.

The oscillograms shown on this figure were made with an amplifier which has seen considerable service in the field during past years. In making these oscillograms, twelve of the amplifiers were available and, since each amplifier had

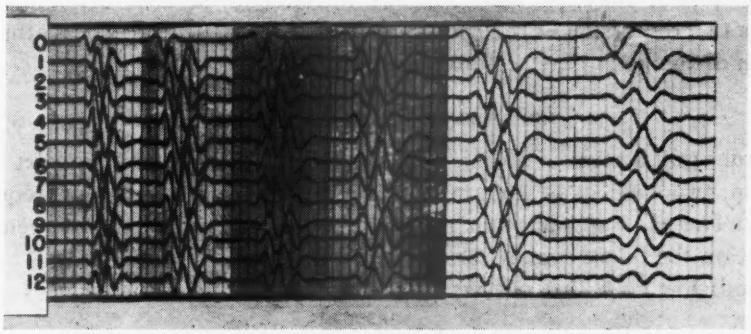

FIG. 5. Output disturbances from conventional amplifiers for true wavelet input.

twelve different filter characteristics, each amplifier has been set on a different filter-switch position. The inputs to the amplifiers were symmetrical velocity-type wavelet forms from a *photo-electric wavelet generator* and are carried on the upper trace which is, of course, free from any filtering. Six different wavelet breadths have been used.

Several features of this record should be noted. In the first place the output form is very much more prolonged than is the input wavelet form. Also, the form is considerably more complicated than the input. These matters obviously result in a more complicated seismogram because of a greater degree of overlapping of reflections and because of a more complicated form for each of the reflections on the seismogram. It will be seen further that a time-pick made on an output form with a particular filtering will not correlate with a time-pick made on an output form of different filtering. This shows rather dramatically why it is not possible to change filter switch positions during a seismic survey.

There is an additional difficulty brought out by these oscillograms which is probably not appreciated by the average operator. As the input wavelet breadth varies, even though the filter setting is held fixed, the time delay of any time-pick on the output form being carried varies widely relative to the center of the input wavelet. Now in actual seismic operations the input wavelet breadth may vary considerably as the party moves about over the area being surveyed, and so the above difficulty must result in serious wanderings of the time-pick on the output form without the operator being in any sense aware of the error.

It may not be out of place to ask "Why, then, do we introduce filtering if the filtering adds an undesirable complication to the seismogram?" The answer, of course, is "to suppress ground roll." It may be well to mention, however, that there are other ways of suppressing ground roll than by filtering in the amplifier. One way is to place the charge deep enough so that the ground roll is not set up. Very excellent reflection seismograms may be obtained with deeply planted shots and flat response amplifiers. The use of deep shots is, of course, expensive, and we resort to filtering as a bad way out of an economic difficulty. If, then, it is necessary or desirable to use other than flat response equipment we must know what equipment may be used without introducing serious distortions. This brings us to a discussion of the conditions under which seismic apparatus will be free from distortion.

DISTORTIONLESS SEISMOGRAPHS

In order that a piece of seismic apparatus may pass a seismic wavelet without distortion, two conditions must be met, within the band of relevant frequencies.

First: The *phase characteristic* must be a *linear* function of the frequency with intercept on the phase axis of zero or an integral multiple of π.

Second: The *amplitude response characteristic* must be of the form

$$A = A_0 e^{kf^2} \tag{23}$$

wherein f is the frequency and A_0 and k are constants.

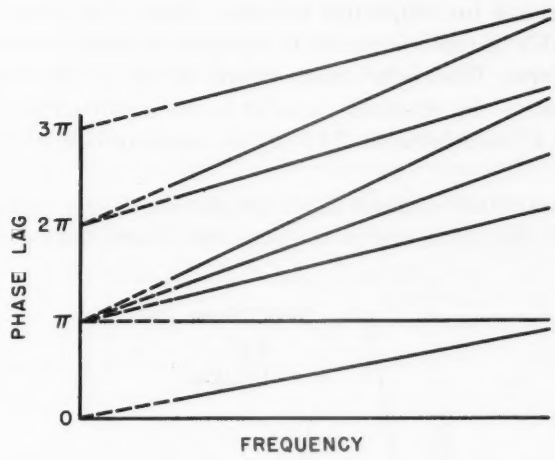

FIG. 6. Examples of phase characteristic curves for distortionless transmission of seismic wavelets.

On Figure 6 the first requirement is illustrated. Any of the phase characteristics shown will serve our needs. If the intercept is zero or an even integral multiple of π the wavelet emerges erect, while if the intercept is an odd integral multiple of π the wavelet emerges inverted. What is particularly bad is for the intercept to lie in between any of the values shown; in which case the form becomes badly skewed. This phase requirement is *not new* and is familiar to all who have worked with transient disturbances.

Relative to the second requirement, which *is new* and which applies specifically to the transmission of these seismic wavelet forms, there are three possibilities as follows:

1. If $k=0$ we have a flat response characteristic and the emergent wavelet is identical with the input wavelet.

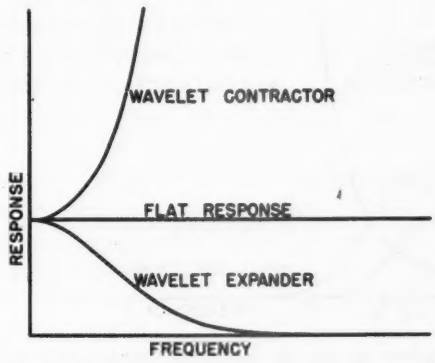

FIG. 7. Amplitude response characteristic curves for distortionless transmission of seismic wavelets.

2. If k is negative the amplitude response characteristic has the same form as the earth's transmission and the wavelet emerges broader but is not distorted in form. This is the characteristic of the wavelet expander.
3. If k is positive the emergent wavelet is not distorted in form but is contracted to a lesser breadth. This is the characteristic of the wavelet contractor.

These three *amplitude response characteristics* are shown on Figure 7.

As the author has often said in the past, the seismic wavelet may be repre-

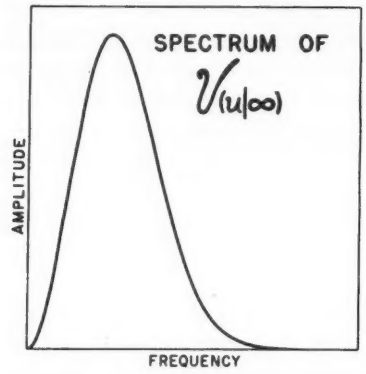

FIG. 8. The frequency spectrum of $\mathcal{V}(u|\infty)$.

sented as the sum of an infinite array of single frequency sinusoidal components, covering the entire range of frequencies from zero to infinite frequency. The amplitudes of the sinusoidal components plotted against the frequency, we call the frequency spectrum of the wavelet. The spectrum of the form $\mathcal{V}(u|\infty)$ is shown on Figure 8. In building up the wavelet form from these single frequency sinusoidal components, at one point all of these components are in phase, and this

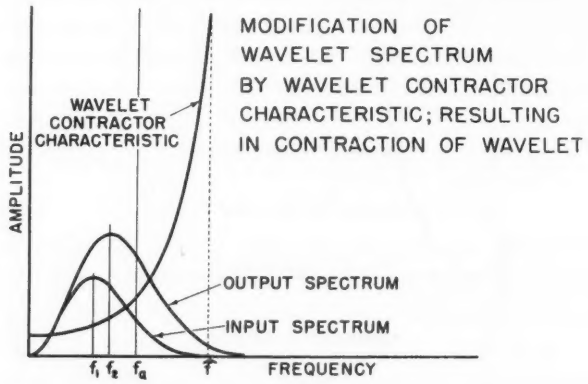

FIG. 9. Chart showing how the wavelet contractor characteristic modifies the spectrum of the wavelet and thereby contracts the wavelet.

accounts for the deep valley at the center of the wavelet. The phase requirement for no distortion, mentioned a moment ago, insures that this in-phase relationship of the components at the wavelet center be maintained as the wavelet passes through the apparatus.

Figure 9 shows how the spectrum of the input wavelet lies with respect to the amplitude response characteristic of the wavelet contractor. Operating against the flank of the rapidly rising characteristic, the high frequency components are amplified to a greater degree than the low frequency components, so that the spectrum of the output wavelet becomes of the shape also shown in the figure. It is because of the specific choice of shape of the response characteristic that the output wavelet spectrum has the same shape as that of the input spectrum except that its peak lies at a higher frequency than the peak of the input spectrum. The spectrum of the input wavelet is

$$\frac{f^2}{f_1^2} \cdot e^{-f^2/f_1^2} \tag{24}$$

wherein f is the frequency of the given sinusoidal component and f_1 is the peak frequency of the spectrum. f_1 is given by

$$f_1 = \frac{\sqrt{6}}{\pi} \cdot \frac{1}{b} \tag{25}$$

where b is the breadth of the wavelet. We may write the wavelet contractor amplitude response characteristic as

$$e^{+f^2/f_a^2} \tag{26}$$

where f_a is a constant of the apparatus. The output wavelet spectrum will be the product of these, or

$$e^{+f^2/f_a^2} \cdot \frac{f^2}{f_1^2} e^{-f^2/f_1^2} = \frac{f_2^2}{f_1^2}\left[\frac{f^2}{f_2^2} \cdot e^{-f^2/f_2^2}\right] \tag{27}$$

wherein

$$\frac{1}{f_2^2} = \frac{1}{f_1^2} - \frac{1}{f_a^2}. \tag{28}$$

In this manner we see that the shape of the output spectrum is the same as that of the input spectrum except for a constant factor of proportionality and the shift of the peak frequency to a greater value.

We may write equation (28) as

$$b_2^2 = b_1^2 - b_a^2 \tag{29}$$

wherein b_1 is the breadth of the input wavelet, b_2 the breadth of the output wave-

let and b_a is a constant to be associated with the amplitude response characteristic of the wavelet contractor.

The analysis in the case of the wavelet expander is similar except for a change in one of the signs, resulting in the formula

$$b_2^2 = b_1^2 + b_a^2. \tag{30}$$

Equations (29) and (30) are the fundamental equations of the wavelet contractor and wavelet expander respectively.

Since a wavelet, in passing through the earth, has the square of its breadth increased by an increment associated with each section of earth passed through, it is seen that there is nothing particularly mysterious about wavelet contraction and wavelet expansion. The wavelet expander, having the same transmission characteristic as a section of the earth, performs the same function as this section of the earth as the wavelet passes through. Similarly, the wavelet contractor is, in fact, an *equalizer*, a term well known to all telephone engineers. The circuit *equalizes* the transmission characteristic of a certain section of the earth and so, in effect, removes it.

WAVELET CONTRACTION

Now what will be the effect upon a seismogram if we contract the wavelets which go to make up a wavelet complex? Figure 10 illustrates the effect which wavelet contraction should have upon the resolution of a wavelet complex. At the upper left there are shown three wavelets with their centers indicated by the vertical lines. On the upper right these wavelets have been added together to form a wavelet complex. The three-fold wavelet composition is not at all in evidence. In fact, there are but two valleys, and these do not lie upon any of the three lines of wavelet centers. If we redraw this complex, using wavelets of half the breadth, we see now that the complex has been resolved, and that the

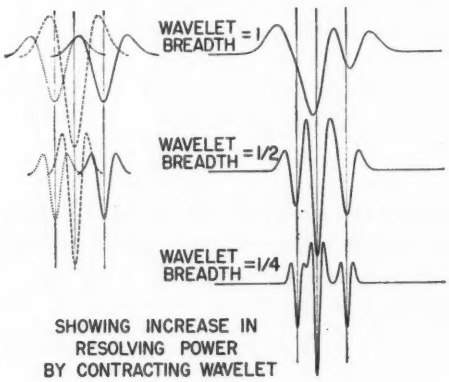

FIG. 10. Chart showing how wavelet contraction increases the resolving power of a seismogram.

FIG. 11. The contraction of a wavelet in a laboratory model of the wavelet contractor.

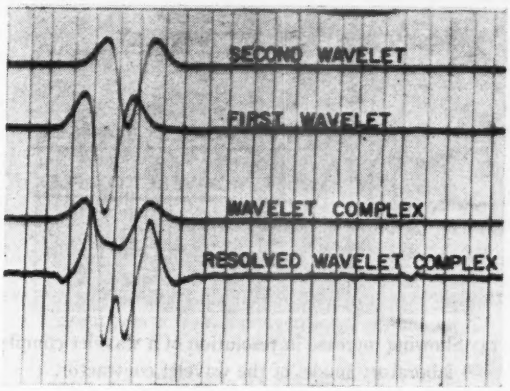

FIG. 12. Showing the resolution of a wavelet-complex by a laboratory model of the wavelet contractor.

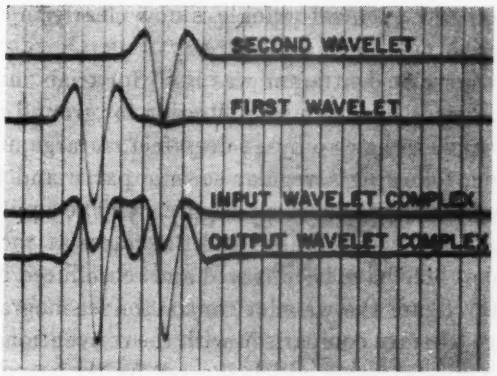

FIG. 13. Showing increase in seismic resolution by laboratory model of the wavelet contractor.

three valleys now lie well placed upon the three lines of centers. Redrawn with wavelets of one quarter of the original breadth, the three wavelets are now clearly seen.

In showing this figure it is not implied that any such great contraction is likely to be realized, but it does show the objective to be sought through wavelet contraction.

Figure 11 shows the practical realization of wavelet contraction with a laboratory circuit, the contraction being to 0.81 of the input wavelet breadth.

Figure 12 shows the resolution of a wavelet complex. Two wavelets, with different arrival times, have been added in a mixing circuit, and then passed through the wavelet contractor. The output shows the complex clearly resolved.

Figure 13 is similar, with the wavelet components not so close together.

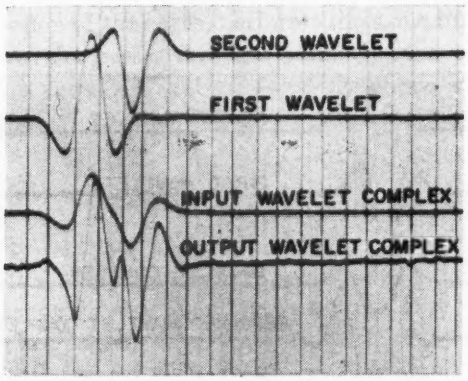

FIG. 14. Showing increase in resolution of a wavelet complex by laboratory model of the wavelet contractor.

Figure 14 shows the effect of contracting wavelets with a different type of wavelet complex. Here we have an erect wavelet following an inverted wavelet with the central wrinkle barely observable in the complex. After passing through the wavelet contractor, the central wrinkle is now clearly in evidence. Compare these forms with the forms shown on Figure 4.

A three-channel wavelet contractor was built for trials in the field. This apparatus also had sufficient low frequency filtering for ground roll suppression, to permit shots to be made in holes only 45 deep feet. A large number of field seismograms were made, following a regular seismic party and taking their shots. Comparison seismograms are shown on Figure 15. The upper seismogram was made with a conventional seismograph, and the traces at 770, 660 and 550 feet distance from the shot hole have been traced and reproduced immediately below. At the bottom of the figure the wavelet contractor seismogram has been reproduced so that a trace by trace comparison with the conventional seismogram may be made. The reflections are very much sharper on the wavelet contractor seismogram, partly because of the avoidance of distortion, and partly because of

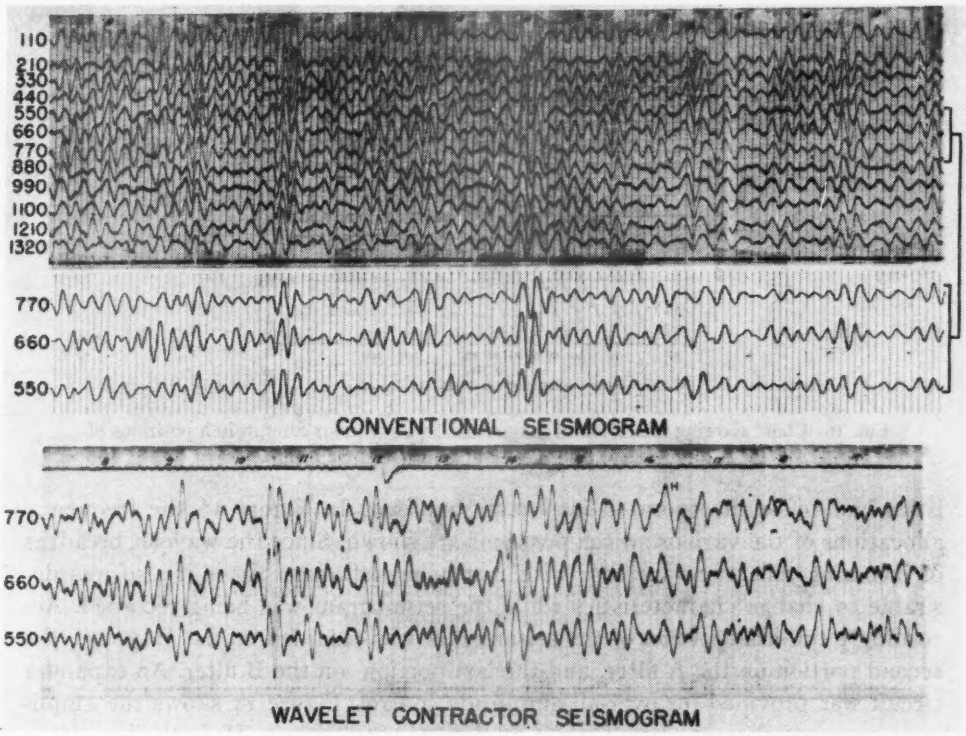

FIG. 15. Comparison of seismogram made with three-trace wavelet contractor in the field with seismogram from a conventional seismograph.

wavelet contraction. This increased sharpness was evident on all the seismograms made on this program.

Encouraged by the excellent performance of this first field model of the wavelet contractor, a full set of instruments was built for the purpose of field evaluation. Since the principal objective of the program was the evaluation of the *principle* of wavelet contraction, it was decided not to attempt ground roll suppression in the amplifiers, but to control ground roll through deep shooting. This permitted greater freedom in amplifier design so that the characteristic response curves could be shaped more closely to the ideal wavelet contractor characteristic.

Now the characteristic of the wavelet contractor cannot rise indefinitely, but must eventually stop rising and be brought back down. This is because of practical limitations of amplifiers and for reasons of noise exclusion. Since only the rising part of the characteristic may be used, it is important that no significant part of the wavelet spectrum extend into the frequency zone in which the characteristic is falling, or serious distortions will result. Since a wide range of input wavelet breadths must be accommodated by the amplifiers, and since no single characteristic will serve all wavelet breadths, a number of character-

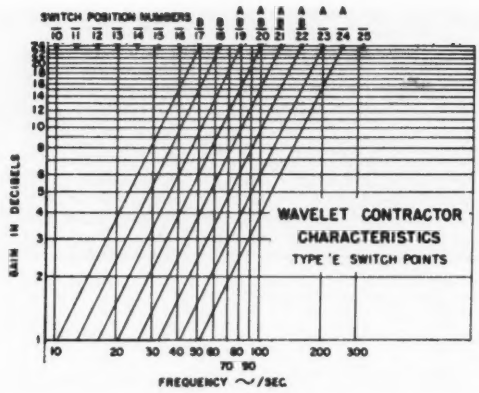
SWITCH POSITION NUMBERS
10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25
GAIN IN DECIBELS
WAVELET CONTRACTOR
CHARACTERISTICS
TYPE 'E' SWITCH POINTS
10 20 30 40 50 60 80 100 200 300
70 90
FREQUENCY ~/SEC

FIG. 16. Chart showing allocation of frequencies to the various filter switch positions of the complete field model of the wavelet contractor.

istics had to be incorporated into each amplifier. In Figure 16 the frequency allocations of the various switch positions are shown. Since the wavelet breadths of incoming reflections increase with increasing reflection times it also was desirable to change characteristics while the seismogram was being recorded. Accordingly the first portion of the seismogram was recorded on flat response, the second portion on the A filter, and the last portion on the B filter. An expander circuit was provided for over-all amplitude control. Figure 17 shows the amplitude response characteristic for one of the switch positions. Here the logarithm of the amplitude has been plotted against the square of the frequency. The characteristic, on this method of plotting, should be a straight line over the usable portion of the characteristic. In Figure 18 one of the characteristic curves has

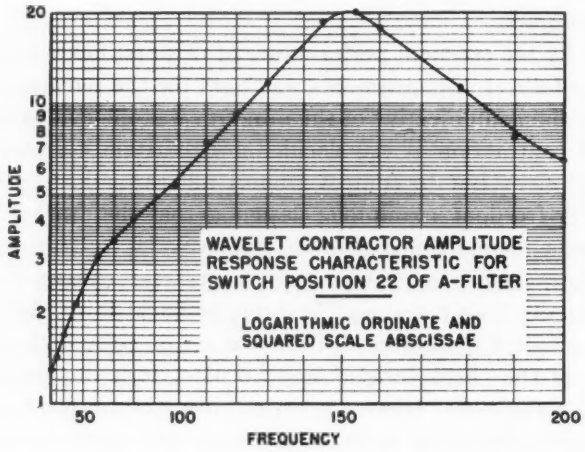

FIG. 17. Logarithm of amplitude response of switch position 22, plotted against the square of the frequency to show linearity over the operating range.

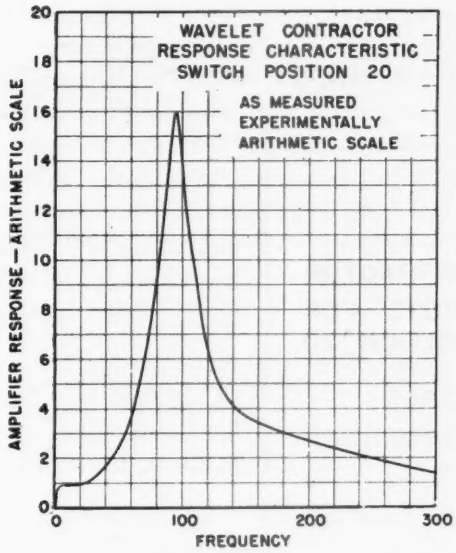

FIG. 18. Wavelet-contractor amplitude response characteristic for switch position 20, plotted on arithmetic scale.

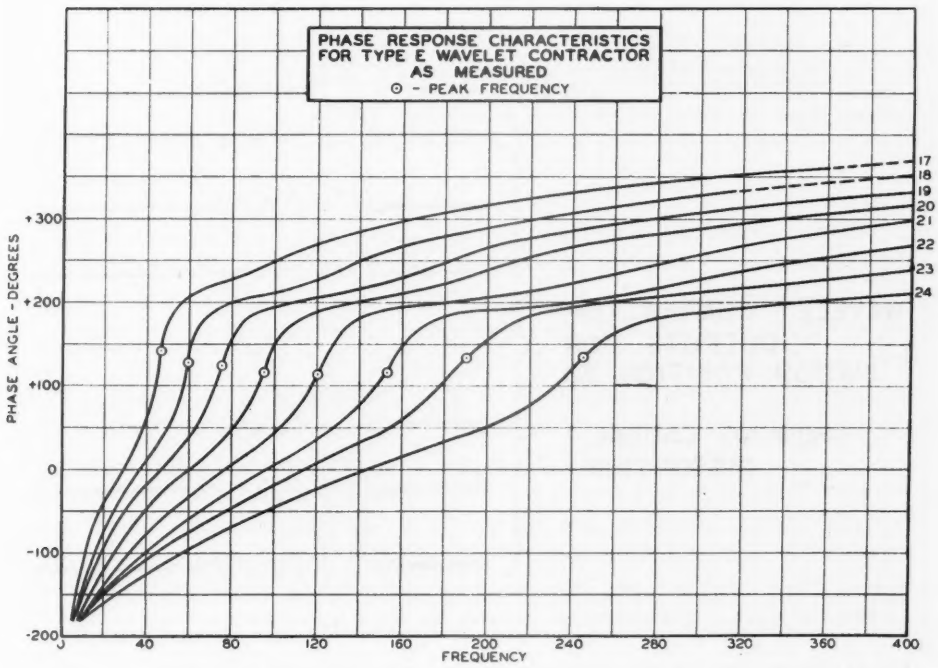

FIG. 19. Measured phase response characteristic curves for the field-model wavelet contractor.

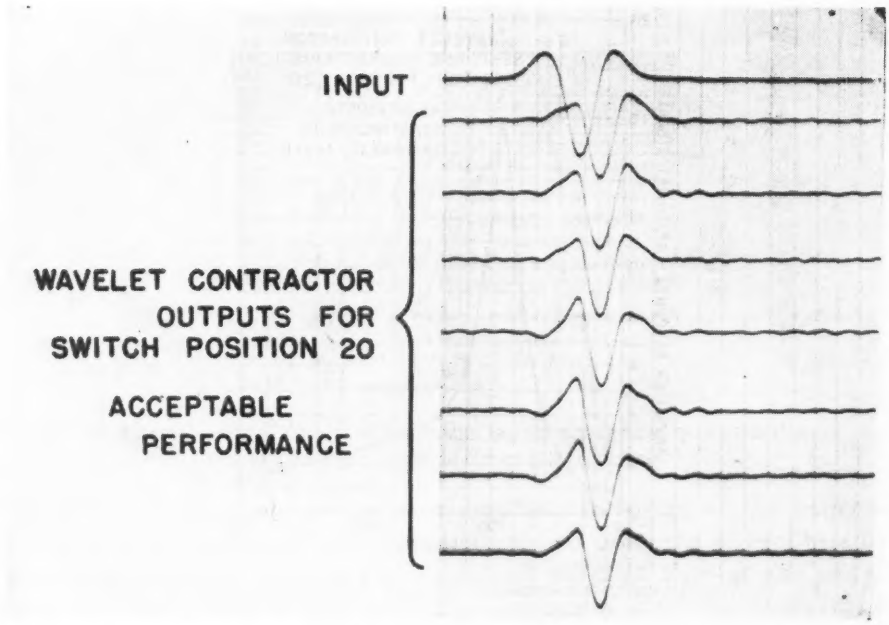

FIG. 20. Output forms for true wavelet input from wavelet contractor with properly chosen switch position for the wavelet breadth involved.

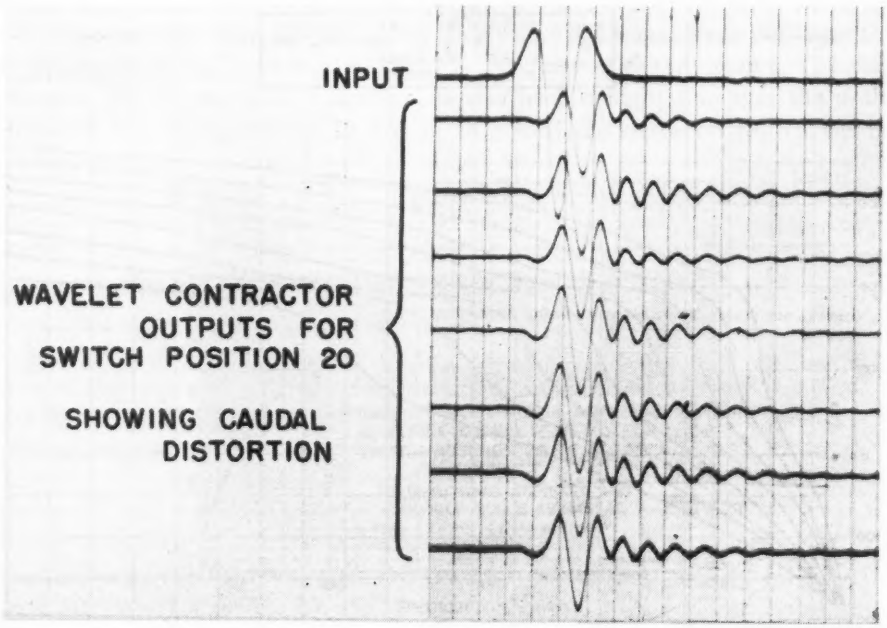

FIG. 21. Output forms for true wavelet input from wavelet contractor with switch position too low for the wavelet breadth involved, showing the development of caudal distortion.

been plotted on arithmetic scale. Only the rising part of the characteristic can be used, and the wavelet spectrum should lie to the left of the peak in order to avoid distortions. This response characteristic has the appearance of a narrow band pass filter but it *must not be used as such.*

In Figure 19 the phase characteristics of the various switch positions are shown. All phase intercepts are in the neighborhood of minus π and the curves are not too far from linear over their operating range.

Figure 20 shows some laboratory studies of wavelet contraction with seven identical amplifiers, for a true wavelet input, and for a properly selected switch position for the particular wavelet breadth involved. Notice the contraction.

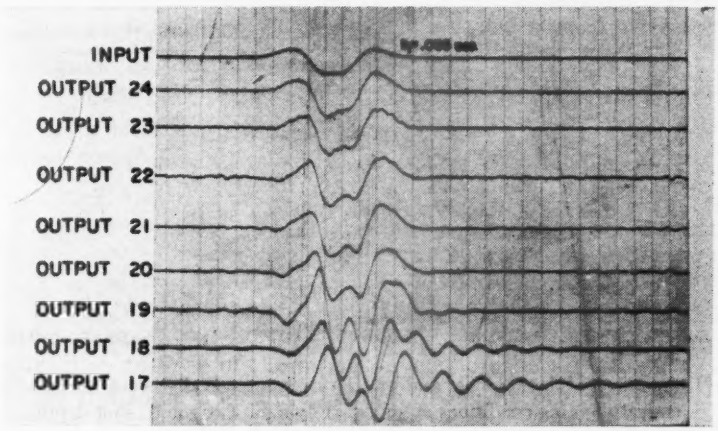

FIG. 22. Output forms for an input in the form of a wavelet complex at the resolution point, showing increase in degree of resolution as switch position is lowered, until caudal distortion develops on the lower two traces.

Figure 21 shows what happens when too narrow a wavelet is used for the switch position selected. In this case the wavelet spectrum extends into the region of the falling part of the characteristic and a *caudal* distortion develops.

Figure 22 shows the resolution of a wavelet complex. The input form is a two-wavelet complex on the verge of resolution but not resolved. Each of the amplifiers has been set on a different switch position. It will be seen that, as lower and lower switch positions are used, better and better resolution of the complex is effected until caudal distortion develops on the lower two traces.

Let us describe briefly the wavelet contractor seismograph which was used in the field evaluation program. The seismograph contained twelve channels, which permitted both sides of the hole to be shot simultaneously with six geophones on each spread. The geophones had natural frequencies around $3\frac{1}{2}$ cycles per second and were damped to $\frac{1}{4}$ of critical damping. The galvanometers had natural frequencies around 400 cycles per second and were damped to 7/10 of critical damping. Each amplifier had a flat response switch position and two

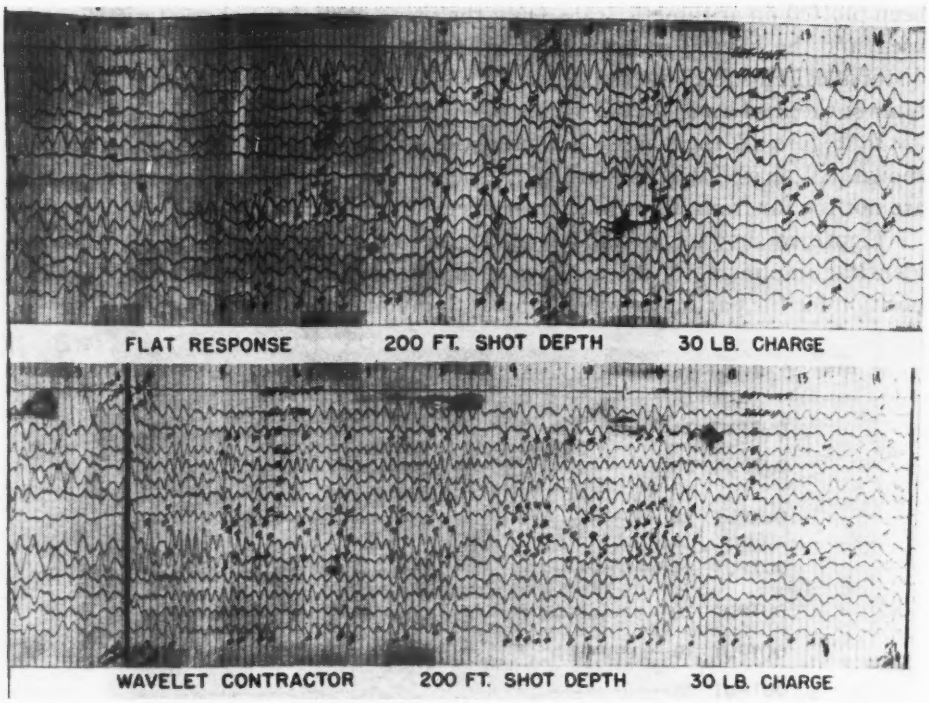

FIG. 23. Comparison of flat response and wavelet contractor field seismograms made under identical shooting conditions of 30 lbs. of dynamite at 200 ft. shot depth.

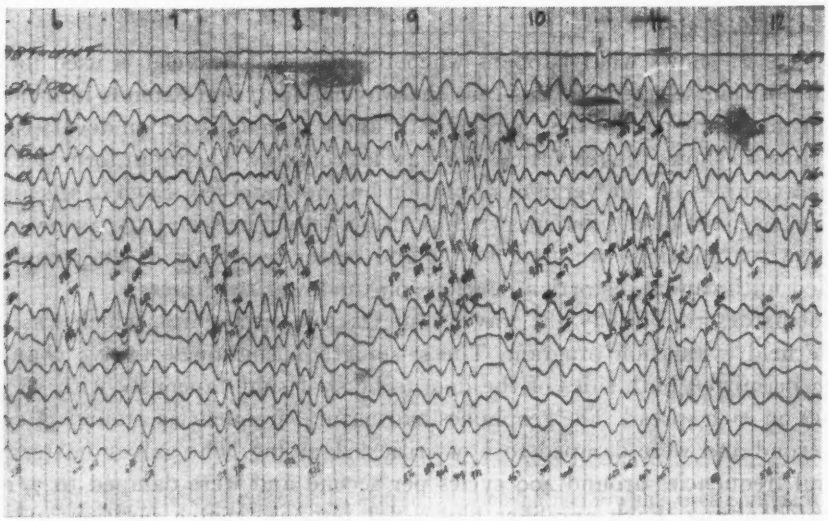

FIG. 24. Enlargement of a portion of the wavelet-contractor seismogram.

wavelet contractor filters—an A filter and a B filter. The A filter carried switch positions 19 to 24 inclusive, and the B filter switch positions 17 to 22 inclusive. The switch position number was ten times the logarithm to base 10 of the peak frequency of the response characteristic. The gain at peak frequency was 16 times the gain at low frequencies.

An evaluation program was carried out in areas in Oklahoma where reflections were generally considered good. As a result of the evaluation program, it was found that depths determined by the wavelet contractor showed closer agreement with subsurface data from well logs than did those determined by conventional seismographs. One particular feature of the wavelet contractor was the demonstration that the truncation of a prominent and well known bed against a major unconformity could be followed to a point 900 feet further than the best conventional seismograph with which it was compared.

Figure 23 shows one of the wavelet contractor seismograms in comparison with a flat response seismogram, both seismograms being recorded under the same shooting conditions; namely, 30 pounds of dynamite at a shot depth of 200 feet.

Figure 24 shows a portion of the wavelet contractor seismogram reproduced on a larger scale.

CONCLUSION

Relative to the degree of wavelet contraction to be realized, it can be said that a contraction to 8/10 of the input wavelet breadth is quite easily realized, and with care and some difficulty this may likely be brought to 7/10. Further contraction will be attended with much greater difficulty. This does not mean that greater contraction cannot be achieved. The difficulty of further contraction is in itself a challenge.

Now relative to the general problem of seismic resolution, the wavelet contractor is not offered as a panacea for all the ills of seismic prospecting. It is definitely a special purpose instrument, to be used where reflections are good by ordinary standards, and where an increase in resolving power is desired for more precise work.

In some areas there are really too many reflections already and, actually, in these areas it may be desirable to lose resolution. In such areas there are possibilities for the wavelet expander, for by expanding the wavelets a greater degree of overlapping occurs and resolution is thereby deliberately reduced. Such a procedure would bring out only a few prominent beds, which should be sufficient for some purposes. One possibility of its application is in areas where reflections are bad because of the presence of hard beds at or near the surface of the earth. These hard beds result in numerous multiple reflections within these beds, producing a prolonged high-frequency disturbance which masks the deeper reflections. On one occasion where such a condition existed, a simple wavelet expander was built and the high frequency disturbance was removed, so that the deeper reflections could be seen.

The instrumental work and field evaluation programs associated with the wavelet contractor development have extended over a number of years. During this period several people have contributed materially to the success of the program. The author wishes particularly to mention:

Mr. Ralph D. Lynn who contributed much to general instrument and equipment development;

Mr. James J. Roark who did the electronic circuit development;

Mr. Stanley E. Giulio who served as computer during the critical evaluation studies;

Mr. W. A. Sorge who served as party chief during the final field evaluation program; and

Mr. R. N. Jolly who served as operator.

REFERENCE

Ricker, Norman (1953) The form and laws of propagation of seismic wavelets, *Geophysics*, vol. 18, pp. 10–40.

GHOST REFLECTIONS CAUSED BY ENERGY INITIALLY REFLECTED ABOVE THE LEVEL OF THE SHOT*

F. A. VAN MELLE† AND K. R. WEATHERBURN†

ABSTRACT

Some experiments are described which demonstrate the occurrence of an initial reflection from above shot level and of a resultant secondary reflection from depth which, by optical analogy, may be termed a ghost reflection. The reflector above shot level was in this case the base of the weathered layer. Reflection coefficients as high as $\frac{2}{3}$ were found in the Pleistocene Beaumont clay surface in Harris County, Texas. With reflection coefficients of this magnitude, the ghost reflections influence the character of seismograms noticeably.

INTRODUCTION

Although the occurrence of a reflection from above the level of the shot was anticipated at the outset of reflection seismology, the phenomenon seems to have been observed on relatively few occasions. It is reported by Leet (1937), who observed in a seismic velocity well survey that the initial kick recurred after a time interval of somewhat less than twice the uphole time, and that the inception of the secondary impetus was 180° out of phase with that of the original impetus. Some experiments to observe this phenomenon by means of a subshot detector are described by Lester (1948); these experiments, however, yielded negative results. In an investigation of fundamental seismic phenomena, Ricker (1951) found reflections from the base of the weathered zone above the level of the shot in Pierre shale surveys in N. E. Colorado. In a study of multiple reflections on the Edwards Plateau, Poulter and Lombardi (1952) presented evidence of reverberations within the Edwards limestone, the surface above the shotpoint as well as the lower boundary of the Edwards acting as excellent reflectors, especially for high frequencies. The possibility of the surface, or a near-surface layer, acting as a reflector has also been inferred in other cases of multiple reflections.

The observations described in the present paper were obtained at Bellaire, Texas, in the summers of 1945 and 1948, and in the winter of 1950. In the first experiments, the occurrence of interference between the direct signal from the shot and a downward reflection immediately following the shot was strongly suggested by the results of a study of the intensity of reflected energy as a function of shot depth. In the later experiments, the downward reflection, or image of the shot, was observed by means of a deeply buried subshot detector, and its effect on the character of reflections from depth was simultaneously examined with an array of seismometers planted at the surface. The experiments made in the winter of 1950 were part of a course in seismic experimentation for geophysical super-

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† Shell Development Co., Houston, Tex.

visors of the operating areas and were undertaken to observe the effect of progressive detonation of the charge on the composite outgoing signal.

OBSERVATIONS WITH SUBSHOT DETECTOR

The experimental arrangement that was used for observing the direct and reflected signals by means of the subshot detector is illustrated in Figure 1. In order to obtain comparable recorded amplitudes for these two signals, the lengths of their travel paths to the subshot detector were made comparable by planting

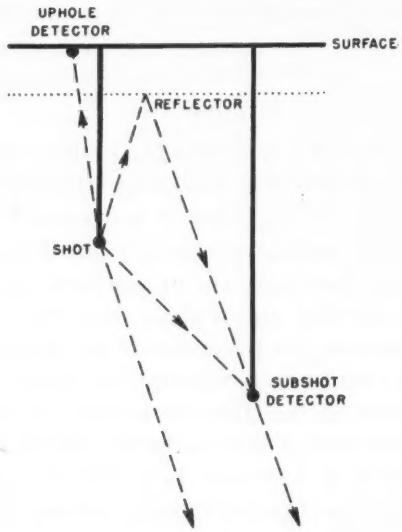

FIG. 1. Experimental arrangement for observations with subshot detector.

the detector well below shot level. To facilitate the planting of the detector, the hole was cased, but the casing was terminated 50 feet above the detector in order to eliminate any disturbance due to its vibration. The depth of the detector below the surface was 407 feet, and its horizontal distance from the shot was approximately 35 feet. An uphole seismometer was also used to assist in locating the position of the reflector above the shot. Shots were fired first at a depth of 25 feet and thereafter at depths increasing by intervals of 10 feet to a depth of 175 feet; additional shots were then fired at intervals of approximately 30 feet to a total depth of 370 feet. The hole was deepened progressively so that all shots could be fired on the bottom.

To ensure satisfactory resolution of the closely spaced direct and reflected signals, no amplifier or filter was used in the recording equipment. The sensitivity of the system was sufficient to permit the detector to be connected to the recording galvanometer through a pure resistance network included to obtain the desired degree of attenuation and correct damping.

For a series of $\frac{1}{4}$-lb charges fired between the depths of 25 feet and 370 feet,

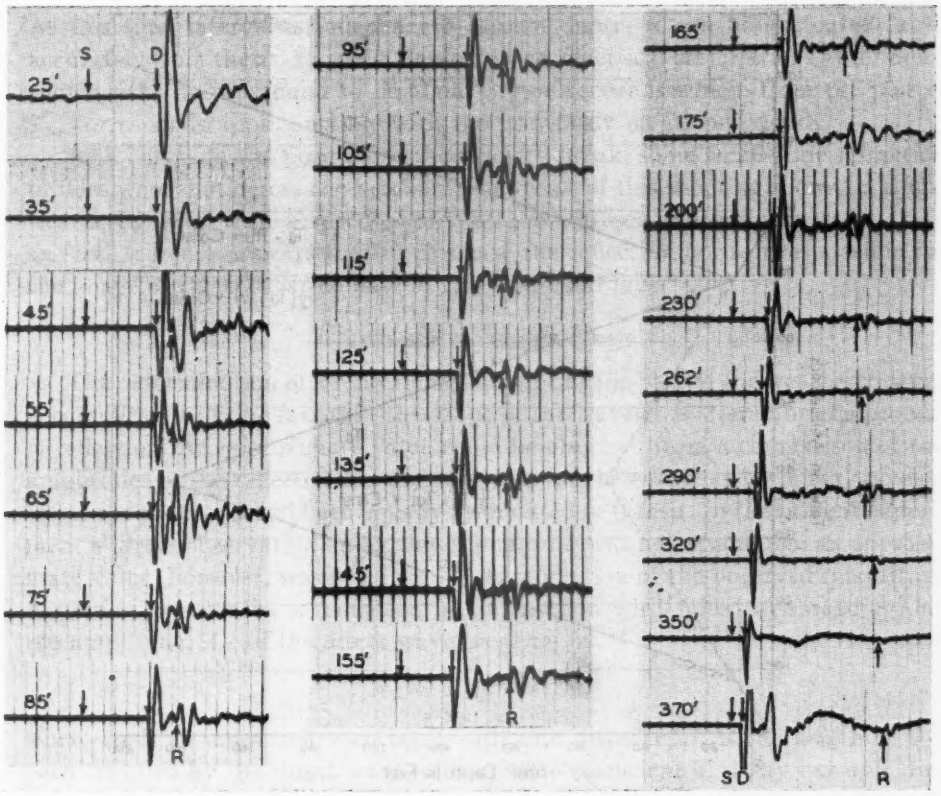

FIG. 2. Signals recorded with a subshot detector at a depth of 407 feet. *S* is the shot break, *D* the direct signal, and *R* the reflection from above the shot.

the signals that were recorded by the subshot detector at a depth of 407 feet are shown in Figure 2. In each case the shot depth is shown to the left of the recorded signal; *S* is the shot break, *D* the direct signal, and *R* the reflection from above the shot. It will be noticed that as the shot depth is increased, the time interval between the direct and reflected signals increases continuously, while the recorded amplitude of the reflection with respect to that of the direct signal decreases continuously. It will be noticed also that there is a 180° phase relation between the two arrivals. On the record obtained by shooting at a depth of 370 feet, the additional event occurring between the direct and reflected signals is a shear wave originating at the shotpoint and traveling with a speed of about one fourth that of the compressional signal, corresponding to a value of about 0.46 for Poisson's ratio.

In addition to the series of $\frac{1}{4}$ lb charges, a series of cap shots was fired to a depth of 165 feet. These shots produced short, high frequency signals and were used for all time measurements as they gave improved resolution of the direct and reflected signals and more precise time values.

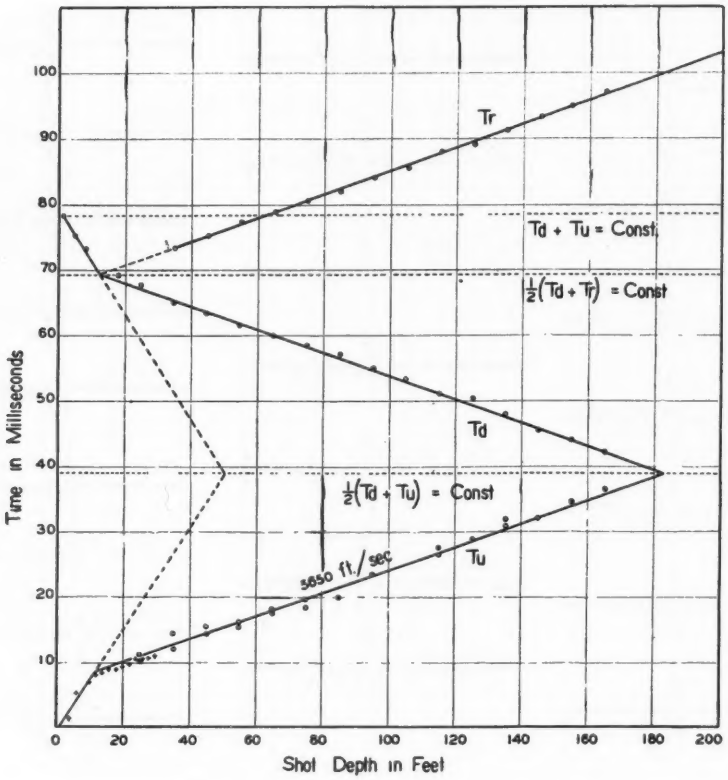

FIG. 3. Travel times of reflected signal (T_r), direct downward signal (T_d), and direct upward signal (T_u) as functions of shot depth.

IDENTIFICATION OF REFLECTOR

A plot of travel times obtained from the series of capshots is shown as a function of shot depth in Figure 3. T_r is the travel time of the event reflected from above the shot; T_d is the travel time of the direct wave, and T_u the uphole time. Additional values of T_u, shown by small crosses, were obtained by shooting cap shots at intervals of 2 feet from a depth of 30 feet to the surface. The travel time curves of T_r, T_d, and T_u are related by symmetry as indicated by the horizontal dotted lines in the figure.

It follows from the geometry that the position of the reflecting horizon is given by the intersection of the curves representing the travel times of the direct and reflected arrivals. It can be seen from Figure 3 that this intersection occurs at a depth of about 12 feet and that it coincides approximately in depth with a velocity break from about 1300 feet/sec to 5650 feet/sec. Alternatively, for vertical incidence, the depth of the reflecting horizon expressed in time below the datum is

$$(T_d + T_u) - 1/2(T_d + T_r).$$

As this time interval is independent of shot depth, it can be evaluated fairly accurately from the average of a number of near-vertical observations at different shot depths. It was found to be about 8.7 milliseconds which, from the plot of T_u, corresponds approximately with the previously mentioned depth.

As a check on the position of the velocity break, some small-scale refraction profiles were shot across the location. The result of this shooting showed a single weathered layer with a speed of about 1400 feet/sec and a thickness of 11 to 12 feet. It hence appears that in this case the reflecting horizon responsible for the image of the shot is the base of the weathered layer.

REFLECTION COEFFICIENT

The determination of a reflection coefficient at the base of the weathered layer is complicated by the fact that the shape of the wavelet is altered by the process of reflection. An approximate value could be obtained from a comparison of the amplitudes of the reflected and direct signals for the case that both had traveled equal distances and had been equally attenuated in transit. In the present experiment a direct observation under these conditions was not attainable; an approximate value, however, was obtained by extrapolation of the observed quantities. Assuming exponential attenuation in conjunction with spherical spreading, let the amplitude, A_d, of the direct wave be given by

$$A_d = A_0[e^{-\alpha S_d}]/S_d,$$

where A_0 is an amplitude associated with zero distance, S_d is the length of the path traveled by the direct wave, and α is the coefficient of decay per unit distance. If A_r is the amplitude of the reflected wave, S_r its travel distance, and K the reflection coefficient, then

$$A_r = A_0K[e^{-\alpha S_r}]/S_r.$$

It follows that

$$(A_r \cdot S_r)/(A_d \cdot S_d) = Ke^{-\alpha(S_r-S_d)}.$$

In Figure 4 is shown a plot of this last relationship on a semi-logarithmic scale. In the hypothetical case of total reflection above the shotpoint and no attenuation other than that due to spherical spreading, the points should fall on a horizontal line through ordinate 1. If there is attenuation other than that due to the geometry, then the points will fall lower with increasing values of S_r-S_d. If this attenuation is exponential with distance and, furthermore, if there is only partial reflection above the level of the shot, then the points will form a straight line whose slope will give the rate of decay of the signal with distance and whose intersection with the vertical coordinate axis will provide the reflection coefficient. The data shown in Figure 4 indicate a value of about $\frac{2}{3}$ for the latter quantity; it is of interest that this reflection coefficient implies that about one-half the energy of the upward signal is reflected at the base of the weathered layer.

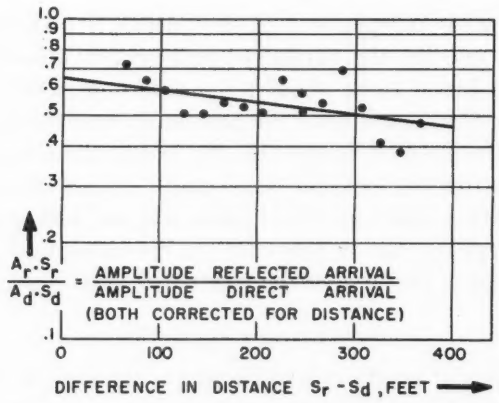

FIG. 4. Approximate determination of reflection coefficient.

If the decay of the signal deviates from the exponential, for instance, as the result of nonlinear processes or because of effects within a few wave lengths of the origin, then the line which averages the points in the semi-logarithmic graph will no longer be a straight line but is likely to be concave upward. Its intersection with the vertical coordinate axis will however furnish the reflection coefficient as before. In this method of determining the reflection coefficient it has been assumed that α and K are independent of frequency; in reality the conditions will, of course, be more complex.

REFLECTIONS FROM DEPTH

Since the shot and its image behave as two separate sources, one may expect that their mutual interference will have a considerable effect on the intensity and

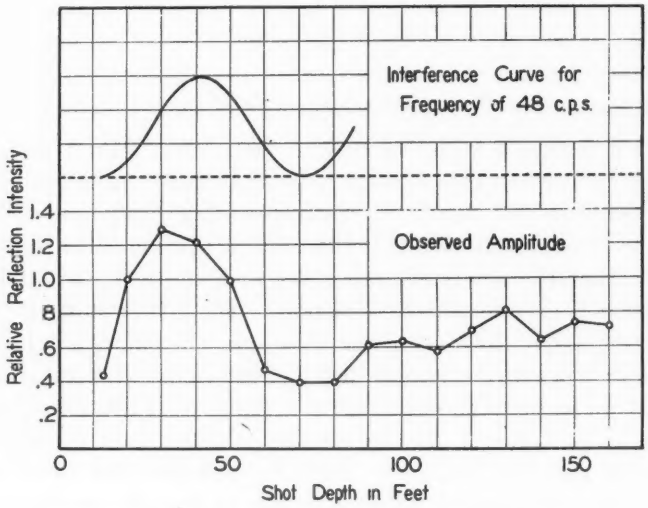

FIG. 5. Average reflection intensity as a function of shot depth.

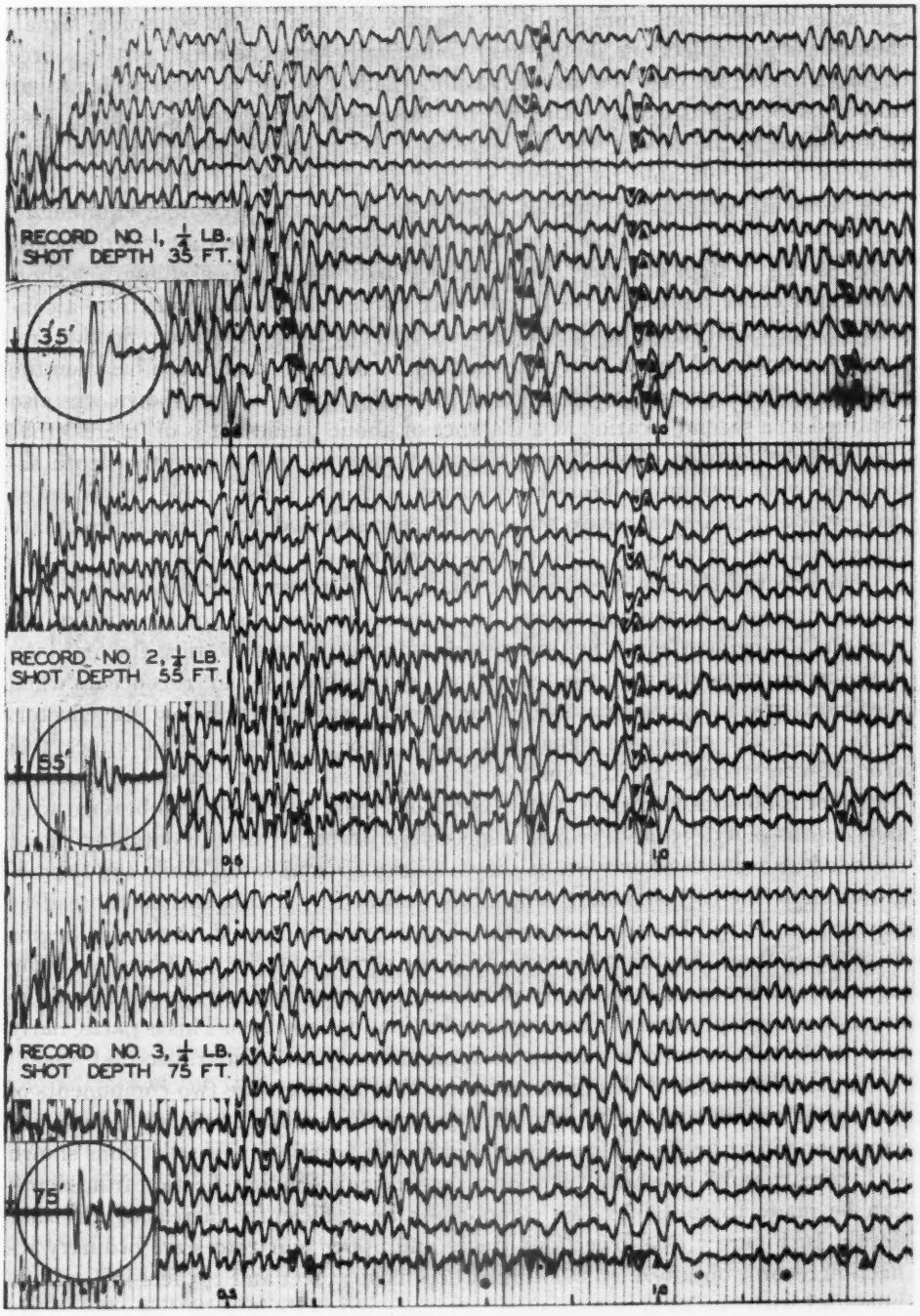

FIG. 6. Records showing the dependence of the character of reflections on the relative positions of the shot and its image.

character of reflections from depth. In the case of a continuous sinusoidal signal, the intensity of reflections should vary sinusoidally with the depth of the source of the signal. In the case of a wavelet, a similar effect should be observable in that range of shot depths in which the two signals are not completely separated. This is illustrated by the lower curve of Figure 5 which represents the average intensity of some 15 correlatable reflections plotted as a function of shot depth. The measurements were made with calibrated detecting and recording equipment, and each shot was the first shot fired on the bottom of a hole that was deepened progressively in steps of 10 feet. A charge of ½-lb dynamite was used for each shot. The upper curve represents the interference curve that would result from a continuous sinusoidal signal having the same frequency as the average reflection frequency, namely, 48 cps. A fairly satisfactory correlation can be seen between the maxima and minima of the two curves. A similar curve to that shown was also obtained at a second location at a distance of about 5 miles. It is of interest that the driller's logs were dissimilar at the two locations: in one case the depth associated with maximum intensity occurred within a considerable thickness of clay, while in the other case this depth corresponded with the approximate center of a sand layer some 35 feet thick overlain by 12 feet of clay.

The effect of the duality of the signal on the character of reflections is of particular interest. The strongest signal that can result from the combination of the shot and its image occurs when the two reinforce each other so that the first loop of the image coincides with the second loop of the direct signal; this occurs when the shot is fired at approximately one-quarter of a wave length below the reflector. In this case the combined signal is a short, smooth wavelet which appears to produce correspondingly the simplest and most satisfactory reflection pattern. This fact is illustrated by the three records of Figure 6 which were obtained with shot depths of 35, 55, and 75 feet respectively. In each case the outgoing signal recorded at a depth of 407 feet is shown in the circular inset, while the seismograms show the corresponding reflections recorded by a conventional spread at the surface. It will be seen that as the shot depth is increased, the image begins to separate from the direct component of the signal, and the combined outgoing signal becomes successively more complicated; correspondingly, as the signal becomes more complicated the quality of reflections deteriorates. This is particularly noticeable in reflections occurring at approximately 0.85 and 1.0 second.

A particular case of this phenomenon is that in which the two components of the signal are sufficiently far apart to produce two separate reflections from the same horizon at depth. This is illustrated by the correlation of reflections shown in Figures 7 and 8 in which it is shown that a single simple reflection from depth can be made to split into two components by sufficiently increasing the shot depth. In Figure 7, the lower four traces and upper four traces are ordinary reflection records obtained by shooting at depths of 35 feet and 175 feet in the same hole and with the same seismometer arrangement. The intermediate traces are single traces from a series of records obtained by shooting at intervals between

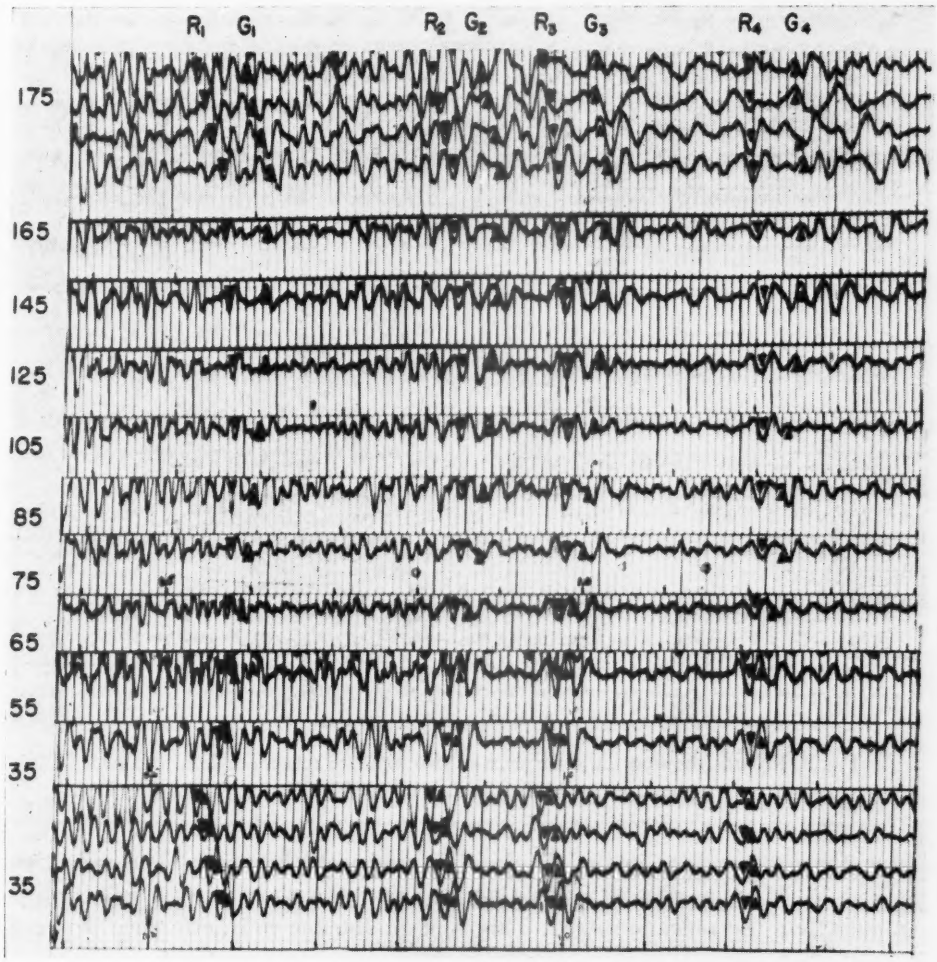

FIG. 7. Records showing the occurrence of two separate reflections from the same horizon at depth. Reflections marked *R* are true reflections; those marked *G* are secondary or ghost reflections. Shot depths are shown to the left of the figure.

the two previously mentioned depths; each of these traces corresponds to the lowest trace of the two 4-trace records. Shot depths are shown to the left of the figure. In the upper record, the reflections marked *R* are true reflections, while those marked *G* are secondary reflections which, by optical analogy, may be termed ghosts. It will be seen that as the shot depth is decreased, each true reflection and its companion ghost merge to form a single reflection at a shot depth of about 35 feet or at a depth corresponding to about one quarter of a wave length below the reflector. The records shown in Figure 7 were obtained during the same experiment as those shown in Figure 2 and, as is to be expected, the time interval between a reflection and its ghost is in each case approximately equal to that be-

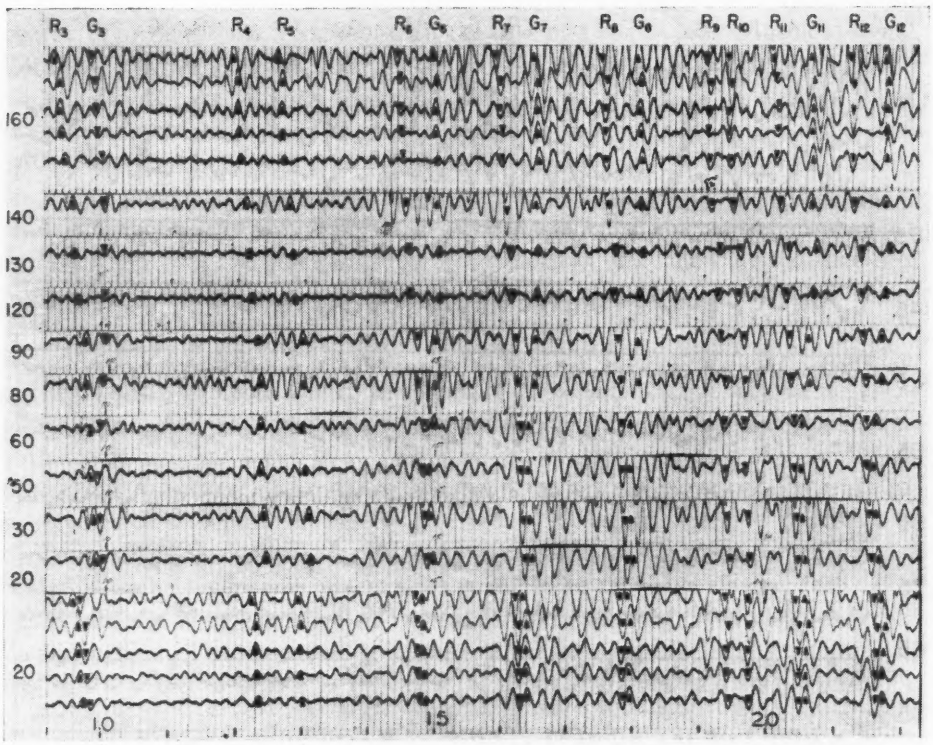

FIG. 8. Records showing the occurrence of two separate reflections from the same horizon at depth. For notation see Figure 7.

tween the shot and its image. Figure 8 is similar to Figure 7. The reflection marked R_{11} is of interest; it will be noticed that the ghost of this reflection is stronger than the reflection itself. This is no doubt due to interference between R_{11} and the ghost of R_{10}.

EXPERIMENTS WITH PROGRESSIVE DETONATION

Finally, some experiments with progressive detonation were made to compare the effect of conventional charges with that of charges consisting of Primacord wound in the form of a vertical helix in such a way that the explosion kept pace with the seismic wave front propagated in a vertical direction. The technique used was a modification of that introduced by Shock (1950) who spaced individual charges at regular intervals along a helix of Primacord in the shot hole. Under the circumstances of the present experiment it was sufficient to use the Primacord without attached charges, and 200 feet of it was coiled to make a charge of 45 feet length.

Some seismograms obtained during these experiments are reproduced in Figure 9. These records show reflections from depth detected with a conventional

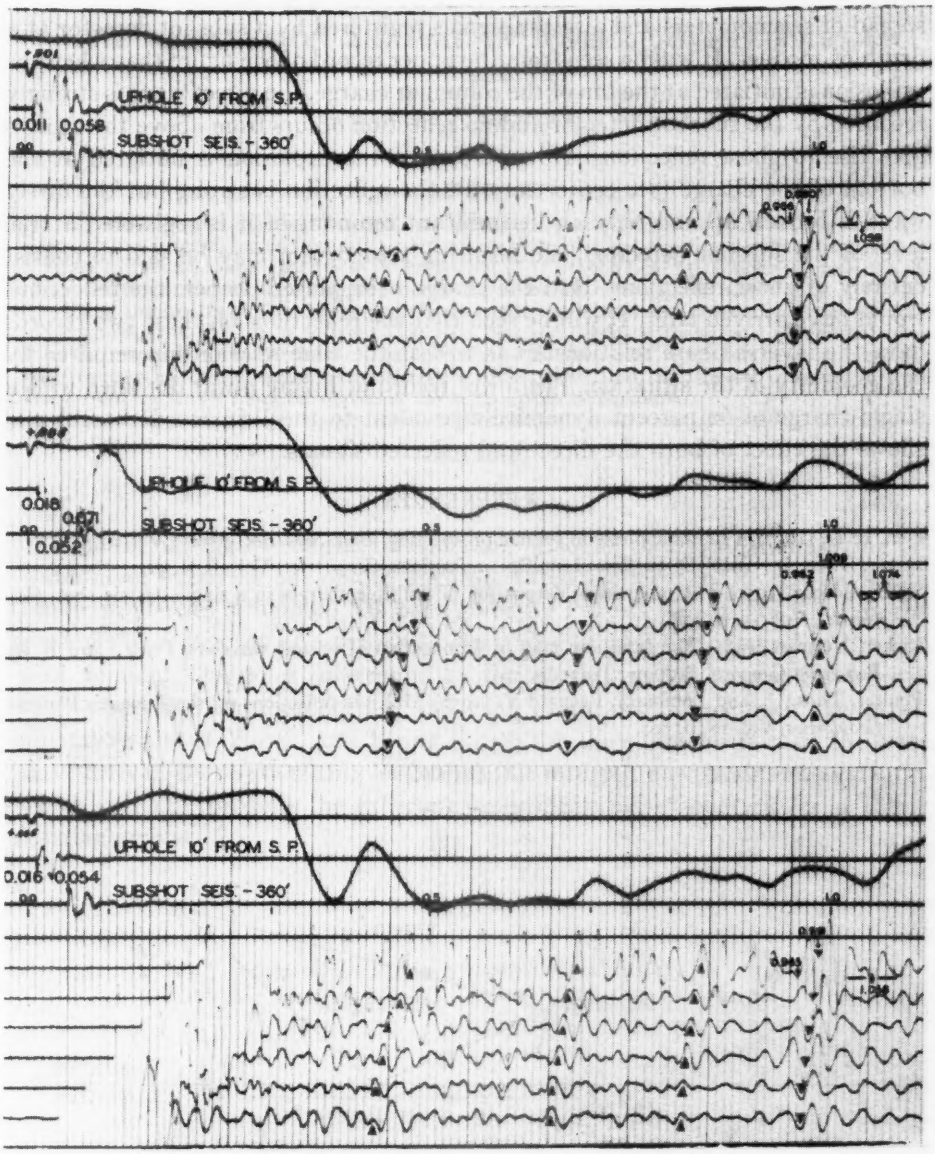

FIG. 9. Seismograms showing the effect of progressive detonation. Center record contains only ghost reflections.

Top record: 200 feet of Primacord between 25 and 70 feet, cap at top.
Center record: 200 feet of Primacord between 19 and 64 feet, cap at bottom.
Lower record: 1¼ lb of 60 percent dynamite at 51 feet.

spread of seismometers and also the signals registered by a subshot detector at a depth of 360 feet. It will be seen from the upper record of the figure that when the explosion is initiated at the top of the columnar charge, the direct wave is strongly recorded by the subshot detector and no reflection occurs from above the shot to give rise to ghost reflections. However, when the explosion is initiated at the bottom of the charge (see center record), the reflection is strong but the direct wave is broken up and only an insignificant remnant of it is registered at the level of the subshot detector. The resulting seismogram may be said to consist entirely of ghost reflections. Had the charge been placed deeper, the reflections would have arrived later. It will be seen that the reflections on these two records have the inverse phase relationship as well as the time relationship required by the geometry of the situation. The lower record of Figure 9 was obtained with a single charge of 60 percent dynamite equivalent to the Primacord charges and shows the effect of both the direct and reflected signals.

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THE REFRACTION ARRIVAL IN WATER COVERED AREAS*

CHARLES B. OFFICER, JR.†

ABSTRACT

A solution is given for the refraction arrival in water covered areas in terms of the evaluation of a branch line integral for an impulsive point source. The physical significance of the mathematical solution is discussed, and experimental verification of the theoretical predictions is presented. The character, frequency, and range dependence of the refraction arrival agree with theory.

Using the results of this theory and the conventional interpretation techniques for refraction seismograms, it is possible to determine the velocities and depths of the seismic refraction horizons from the record of a single receiver. The velocities of the refraction layers can be determined from the frequency of the refraction arrivals, the depth of water, and the velocity of sound in water. Then, from the travel times the depths of the horizons can be computed.

This method could be of importance in reconnaissance measurements of geologic structure over the continental shelves.

INTRODUCTION

The formal theory for the transmission of sound in a system consisting of a water layer overlying one or two unconsolidated sedimentary layers (having the elastic properties of liquids) has been given by Pekeris (1948). His solution consists of the evaluation of a series of poles and a branch line integral in the complex domain. The poles correspond to the normal modes of propagation with their dispersive wave properties, and their evaluations agree with the experimental results of Worzel and Ewing (1948) for the characteristics of the water wave arrival. By re-examining his branch line integral, one obtains an evaluation which correctly predicts the experimentally measured characteristics of the refraction arrival.

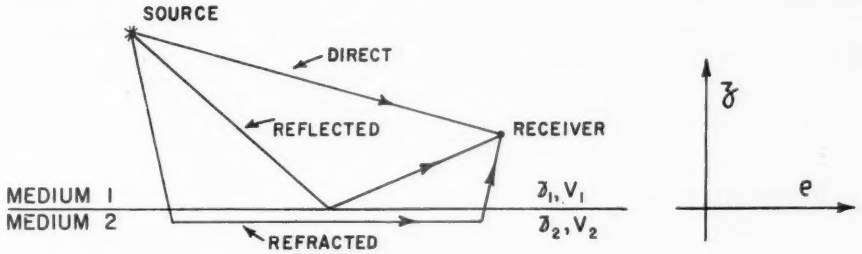

FIG. 1 Direct-, reflected-, and refracted-wave paths.

THEORY OF THE REFRACTION ARRIVAL ACROSS A SINGLE BOUNDARY

The solution of the problem of wave propagation from a point source in a semi-infinite medium of velocity v_1, overlying a semi-infinite medium of higher

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velocity, v_2, has been given by Jeffreys (1926) and by Muskat (1933). From their analysis three waves are obtained—the direct wave from source to receiver, the reflected wave from the interface between the two media, and the refracted wave, incident and emergent in the first medium at the critical angle and travelling in the second medium parallel to the interface (see Figure 1). As the solution of this problem has a close relation to that of refraction in water covered areas, it will be reviewed briefly here, following the method of Muskat (1933).

Let ρ, z be the cylindrical coordinates with source located at (0, h) and let γ_1 and γ_2 denote the densities of the two media respectively. Then the displacement potential, Φ, will be described by the differential equation

$$\left(\nabla^2 + \frac{\omega^2}{v^2}\right)\Phi = 0 \tag{1}$$

where ω is the circular frequency and Φ is related to the displacement components in the z and ρ directions by

$$w = \frac{\partial \Phi}{\partial z} \quad \text{and} \quad q = \frac{\partial \Phi}{\partial \rho}. \tag{2}$$

Fundamental solutions of equation (1) are given by

$$\begin{aligned} z > 0 \qquad & \Phi = e^{\alpha z} J_0(\xi\rho) \\ z < 0 \qquad & \Phi = e^{\bar{\alpha} z} J_0(\xi\rho) \end{aligned} \tag{3}$$

where

$$\alpha^2 - \xi^2 + \frac{\omega^2}{{v_1}^2} = 0 \quad \text{and} \quad \bar{\alpha}^2 - \xi^2 + \frac{\omega^2}{{v_2}^2} = 0. \tag{4}$$

The source can be expressed by

$$\Phi_0 = \frac{e^{i(\omega/v_1)[\rho^2 + (h-z)^2]^{1/2}}}{[\rho^2 + (h-z)^2]^{1/2}} \tag{5}$$

or in integral form by

$$\Phi_0 = \int_0^\infty \frac{e^{-\alpha(h-z)} J_0(\xi\rho)\xi d\xi}{\alpha}. \tag{6}$$

The complete solution, satisfying the boundary conditions at infinity, will then be

$$\begin{aligned} z > 0 \qquad & \Phi_1 = \Phi_0 + \int_0^\infty A(\xi) e^{-\alpha z} J_0(\xi\rho) d\xi \\ z < 0 \qquad & \Phi_2 = \int_0^\infty B(\xi) e^{\bar{\alpha} z} J_0(\xi\rho) d\xi \end{aligned} \tag{7}$$

where A and B are arbitrary functions determined by the boundary conditions at $z=0$,

$$\frac{\partial \Phi_1}{\partial z} = \frac{\partial \Phi_2}{\partial z} \quad \text{and} \quad \gamma_1 \Phi_1 = \gamma_2 \Phi_2 \tag{8}$$

resulting in

$$z > 0 \qquad \Phi_1 = \Phi_0 + \int_0^\infty \frac{\xi(\alpha k - \bar{\alpha})}{\alpha(\alpha k + \bar{\alpha})} e^{-\alpha(h+z)} J_0(\xi\rho) d\xi \tag{9}$$

$$\Phi_2 = 2\int_0^\infty \frac{\xi e^{\bar{\alpha}z - \alpha h}}{\alpha k + \bar{\alpha}} J_0(\xi\rho) d\xi \tag{10}$$

where $k=\gamma_2/\gamma_1$.

The second term of Φ_1 can be evaluated in the complex plane as two branch line integrals. The first branch line integral around the branch point $\alpha=0$ gives the reflected wave

$$\Phi_{r_1} = -\frac{1}{\rho} e^{-i(\omega/v_1)[\rho+(h+z)^2/2\rho]} \tag{11}$$

and the second integral around the branch point $\bar{\alpha}=0$ gives the refraction wave

$$\Phi_{r_2} = -\frac{2iv_1^2}{kv_2\omega\beta^2\rho^2} e^{-i\omega[\rho/v_2+\beta(h+z)/v_1]} \tag{12}$$

where $\beta=(1-v_1^2/v_2^2)^{1/2}$. In the above evaluation the approximation has been made that ρ is large compared with h and z so that the expression $\rho+(h+z)^2/2\rho$ is an approximation for $(\rho^2+(h+z)^2)^{1/2}$. Generalizing the above solutions to an arbitrary pulse $f(t)$ gives

$$\Phi_{r_1} = \frac{-1}{2\pi\rho}\int_{-\infty}^\infty d\omega \int_0^\infty f(\mu) e^{i\omega[\mu+t-\rho/v_1-(h+z)^2/2\rho v_1]} d\mu \tag{13}$$

and

$$\Phi_{r_2} = \frac{-iv_1^2}{\pi k v_2 \beta^2 \rho^2}\int_0^\infty \frac{d\omega}{\omega}\int_0^\infty f(\mu) e^{i\omega[\mu+t-\rho/v_2-\beta(h+z)/v_1]} d\mu. \tag{14}$$

The refraction wave, equation (14), in this case is distorted with respect to the initial wave in such a way that its velocity components resemble the displacement components of the initial wave. It does not have any frequency selective characteristics except what may be in the initial wave.

The plane wave solution for this problem does not yield a refraction arrival, for it is only when there are waves spreading out from a point source that there

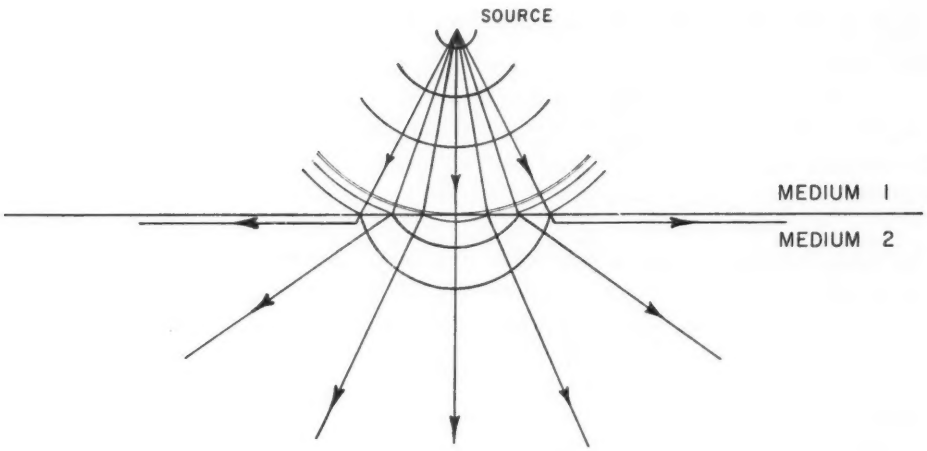

FIG. 2. Refraction at a boundary.

will be a continuum of energy travelling parallel to the interface in the second medium, see Figure 2.

THEORY OF THE REFRACTION ARRIVAL IN A TWO LAYERED MEDIA

Following Pekeris (1948) the formal solution for sound propagation in a water layer underlain by a uniform "liquid" bottom can be given as follows. Let ρ_1 and ρ_2 be the densities of the water and the bottom respectively and c_1 and c_2 be the velocities respectively with $c_2 > c_1$, and let d = depth of the source, z = depth of the receiver, and H = depth of water. Then, the velocity potential, Φ, must satisfy the differential equations

$$\nabla^2\Phi = \frac{1}{c_1^2}\frac{\partial^2\Phi}{\partial t^2}$$

in the water, and (15)

$$\nabla^2\Phi = \frac{1}{c_2^2}\frac{\partial^2\Phi}{\partial t^2}$$

in the bottom where Φ is related to the acoustic pressure, p, and the vertical and horizontal velocity components, w and u, by the relations

$$p = \rho\frac{\partial\Phi}{\partial t}, \quad w = -\frac{\partial\Phi}{\partial z}, \quad \text{and} \quad u = -\frac{\partial\Phi}{\partial r}. \tag{16}$$

Fundamental solutions of equations (15) and (16) are

$$\Phi = e^{i\omega t}J_0(kr)F(z)G(k) \tag{17}$$

where F is given by the following for regions 1, 2, and 3 of Figure 3,

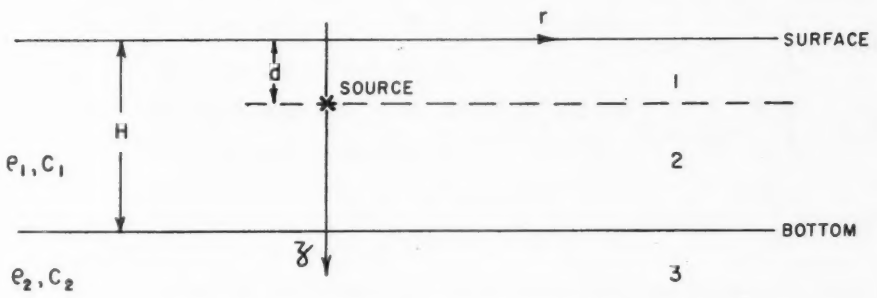

FIG. 3. Geometry of source in water layer of thickness H.

$$\begin{aligned} F_1 &= A \sin \beta_1 z \\ F_2 &= B \sin \beta_1 z + C \cos \beta_1 z \\ F_3 &= De^{-i\beta_2 z} \end{aligned} \tag{18}$$

satisfying the boundary conditions at infinity and at $z=0$. β_1 and β_2 are given by

$$\begin{aligned} \beta_1 &= \sqrt{\frac{\omega^2}{c_1^2} - k^2} && k < \frac{\omega}{c_1} \\ &= -i\sqrt{k^2 - \frac{\omega^2}{c_1^2}} && k < \frac{\omega}{c_1} \\ \beta_2 &= \sqrt{\frac{\omega^2}{c_2^2} - k^2} && k < \frac{\omega}{c_2} \\ &= -i\sqrt{k^2 - \frac{\omega^2}{c_2^2}} && k < \frac{\omega}{c_2}. \end{aligned} \tag{19}$$

At $z=H$, the boundary conditions

$$\rho_1 F_1 = \rho_2 F_2 \quad \text{and} \quad \frac{\partial F_2}{\partial z} = \frac{\partial F_3}{\partial z} \tag{20}$$

must be satisfied, and at $z=d$ the conditions

$$F_1 = F_2 \tag{21}$$

and

$$\frac{\partial F_1}{\partial z} - \frac{\partial F_2}{\partial z} = 2k \tag{22}$$

must be satisfied. Condition (22) insures a point source at $z=d$ when Φ is integrated over k from 0 to ∞ (Press and Ewing, 1950). Substituting (20), (21), and (22) into (18) and integrating over k from 0 to ∞ gives

$$\Psi_1 = 2\int_0^\infty J_0(kr)\,kdk\,\frac{\sin\beta_1 z}{\beta_1}\left[\frac{\beta_1\cos\beta_1(H-d)+ib\beta_2\sin\beta_1(H-d)}{\beta_1\cos\beta_1 H+ib\beta_2\sin\beta_1 H}\right] \tag{23}$$

$$\Psi_2 = 2\int_0^\infty J_0(kr)\,kdk\,\frac{\sin\beta_1 d}{\beta_1}\left[\frac{\beta_1\cos\beta_1(H-z)+ib\beta_2\sin\beta_1(H-z)}{\beta_1\cos\beta_1 H+ib\beta_2\sin\beta_1 H}\right] \tag{24}$$

$$\Psi_3 = 2b\int_0^\infty J_0(kr)\,kdk\,\frac{\sin\beta_1 d e^{-i\beta_2(z-H)}}{\beta_1\cos\beta_1 H+ib\beta_2\sin\beta_1 H} \tag{25}$$

where Φ is related to Ψ by $\Phi = e^{i\omega t}\Psi(r, z, \omega)$ and where $b = \rho_1/\rho_2$.

Ψ_2 (or Ψ_1) can most easily be evaluated in the complex k-plane (see Figure 4). The lines drawn from k_1 and k_2 parallel to the negative imaginary

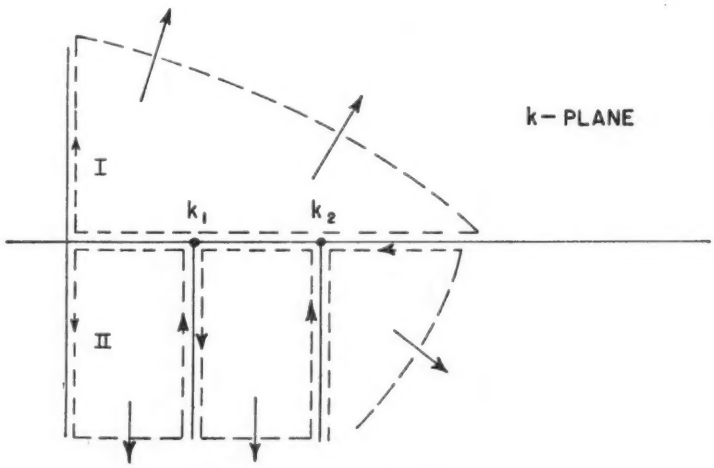

FIG. 4. Branch lines in complex k-plane corresponding to multiple-valued fractions β_1 and β_2.

axis are the branch lines corresponding to the multiple-valued functions β_1 and β_2 where $k_1 = \omega/c_1$ and $k_2 = \omega/c_2$. Substituting $2J_0(kr) = H_0^{(1)}(kr) + H_0^{(2)}(kr)$ into (24), where $H_0^{(1)}$ and $H_0^{(2)}$ are the first and second Hankel Functions respectively, and integrating $H_0^{(1)}$ over path I in Figure 4, and $H_0^{(2)}$ over path II gives the desired integral in terms of the sum of the residues and the two branch line integrals. $H_0^{(1)}$ vanishes at infinity in the first quadrant and $H_0^{(2)}$ in the fourth quadrant, and the integrals along the imaginary axis cancel since $H_0^{(1)}(iq) = -H_0^{(2)}(-iq)$. The first branch line integral, corresponding to $\beta_1 = 0$, has zero value since F has the same value on both sides of the branch line. The residues give the dispersive normal mode wave trains and are discussed fully by Pekeris (1948) both for a periodic point source and for the more general case of an explosive point source. The interest in this paper is in the evaluation of the second branch line integral, corresponding to $\beta_2 = 0$.

Let us designate this integral by Υ; then

$$\Upsilon = \int_{-i\infty}^{k_2} H_0^{(2)}(kr)\left[F(\beta_1, \beta_2) - F(\beta_1, -\beta_2)\right]kdk$$

$$= -2ib\int_{-i\infty}^{k_2} H_0^{(2)}(kr)\,\frac{\beta_2 \sin(\beta_1 d)\sin(\beta_1 z)}{\beta_1^2\cos^2(\beta_1 H) + b^2\beta_2^2\sin^2(\beta_1 H)}\,kdk. \tag{26}$$

Since $H_0^{(2)}$ vanishes exponentially for large imaginary parts of its argument, the value of the integrand is appreciable only when the argument of $H_0^{(2)}$ is small. Then, changing the variable of integration to

$$k = \frac{\omega}{c_1}\eta = k_1\eta \tag{27}$$

where

$$\eta = \frac{c_1}{c_2} - i\theta \tag{28}$$

over the path of integration, we will have for θ small,

$$\beta_1 = \sqrt{k_1^2 - k^2} = k_1(1-\eta^2)^{1/2} \approx k_1\left(1 - \frac{c_1^2}{c_2^2}\right)^{1/2} = k_1\mu \tag{29}$$

$$\beta_2 = \sqrt{k_2^2 - k^2} = k_1\left(\frac{c_1^2}{c_2^2} - \eta^2\right)^{1/2} \approx k_1\left(2i\theta\frac{c_1}{c_2}\right)^{1/2} = k_1\left(2\theta\ \frac{c_1}{c_2}\right)e^{i(\pi/4)} \tag{30}$$

$$H_0^{(2)}(kr) = H_0^{(2)}(k_1 r\eta) = \sqrt{\frac{2c_2}{\pi k_1 r c_1}}\,e^{i(\pi/4 - k_2 r)}e^{-k_1 r\theta} \tag{31}$$

and

$$\beta_1^2\cos^2(\beta_1 H) + b^2\beta_2^2\sin^2(\beta_1 H) \approx \beta_1^2\cos^2(\beta_1 H) = k_1^2\mu^2\cos^2(k_1\mu H) \tag{32}$$

where $\mu = (1 - c_1^2/c_2^2)^{1/2}$. Since β_2 is very small, the approximation to be given in equation (33) is valid generally, except in the regions of zeros of $\cos(\beta_1 H)$. Substituting (28), (29), (30), (31), and (32) into (26) gives

$$\Upsilon = \frac{4ibk_2}{\sqrt{\pi k_1 r}}\,\frac{\sin(k_1\mu d)\sin(k_1\mu z)}{\mu^2\cos^2(k_1\mu H)}\,e^{-ik_2 r}\int_0^\infty \theta^{1/2}e^{-k_1 r\theta}d\theta$$

$$= \frac{2ibk_2}{(k_1 r)^2}\,\frac{\sin(k_1\mu d)\sin(k_1\mu z)}{\mu^2\cos^2(k_1\mu H)}\,e^{-ik_2 r}. \tag{33}$$

The case of principal interest is that for which equation (33) is generalized to a pulse. As representative of an explosion, we shall take an exponential pulse of the form

$$\begin{aligned} f(t) &= e^{-\lambda t} \qquad t > 0 \\ &= 0 \qquad\quad t < 0 \end{aligned} \tag{34}$$

where $f(t)$ can be given by the Fourier integral

$$f(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \frac{e^{i\omega t}}{(\lambda + i\omega)}\, d\omega. \tag{35}$$

Then the expression for the generalized branch line integral, T, will be

$$\begin{aligned} T &= \frac{1}{2\pi}\int_{-\infty}^{\infty} \frac{\Upsilon(r, z, \omega)}{\lambda + i\omega} e^{i\omega t} d\omega \\ &= \frac{1}{2\pi}\int_{-\infty}^{\infty} \frac{2ibk_2}{(k_1 r)^2} \frac{\sin(k_1\mu d)\sin(k_1\mu z)}{\mu^2\cos^2(k_1\mu H)} \frac{e^{i[\omega t - k_2 r]}}{(\lambda + i\omega)} d\omega. \end{aligned} \tag{36}$$

This integral will have its major contributions at values of ω satisfying the equation

$$\cos(k_1\mu H) = 0. \tag{37}$$

However, at these points the approximation of equation (32) will no longer be valid. That expression will then be given by

$$\begin{aligned} &\beta_1^2\cos^2(\beta_1 H) + b^2\beta_2^2\sin^2(\beta_1 H) \\ &\quad \approx b^2\beta_2^2\sin^2(\beta_1 H) = b^2k_1^2\left(2\theta\frac{c_1}{c_2}\right)e^{i(\pi/4)}\sin^2(k_1\mu H). \end{aligned} \tag{38}$$

Substituting (38) into (26) gives for Υ_0,

$$\begin{aligned} \Upsilon_0 &= \frac{2k_2c_2}{bc_1\sqrt{\pi k_1 r}} \frac{\sin(k_1\mu d)\sin(k_1\mu z)}{\sin^2(k_1\mu H)} \int_0^{\infty} \theta^{-1/2} e^{-k_1 r\theta}\, d\theta \\ &= \frac{2c_2k_2}{bc_1k_1 r} \frac{\sin(k_1\mu d)\sin(k_1\mu z)}{\sin^2(k_1\mu H)} e^{-ik_2 r} \\ &= \frac{2}{br} \frac{\sin(k_1\mu d)\sin(k_1\mu z)}{\sin^2(k_1\mu H)} e^{-ik_2 r} \end{aligned} \tag{39}$$

and for T_0,

$$T_0 = \frac{1}{2\pi}\int_{-\infty}^{\infty} \frac{2}{br} \frac{\sin(k_1\mu d)\sin(k_1\mu z)}{\sin^2(k_1\mu H)} \frac{e^{i[\omega t - k_2 r]}}{(\lambda + i\omega)} d\omega \tag{40}$$

where T_0 is to be evaluated in the neighborhood of values of the integrand ω_0 satisfying equation (37). For the source and receiver on the bottom, i.e., $z = d = H$, this will be of the form,

$$\begin{aligned} T_0 &= \sum_{\omega_0} \frac{A_0}{\pi br} \frac{\cos\left[\omega_0 t - k_{20} r - \tan^{-1}\left(\frac{\omega_0}{\lambda}\right)\right]}{(\lambda^2 + \omega_0^2)^{1/2}} && t \geqq \frac{r}{v_2} \\ &= 0 && t < \frac{r}{v_2}. \end{aligned} \tag{41}$$

T_0 is the expression for the velocity potential of the refraction arrival from an impulsive point source. It is a train of waves travelling with the velocity of the lower medium, $c_2 = \omega_0/k_{20}$. It is composed of the set of discrete frequencies, ω_0. It varies in range as r^{-1}, as contrasted with r^{-2} for the steady-state case; and its amplitude is greater the greater the density contrast between the two media. The $(\lambda^2+\omega_0^2)^{1/2}$ term merely expresses the excitation of the source at the frequencies ω_0.

It has come to the author's attention that Sato (1952) has obtained a similar solution for the refracted SH waves in a single layered medium.

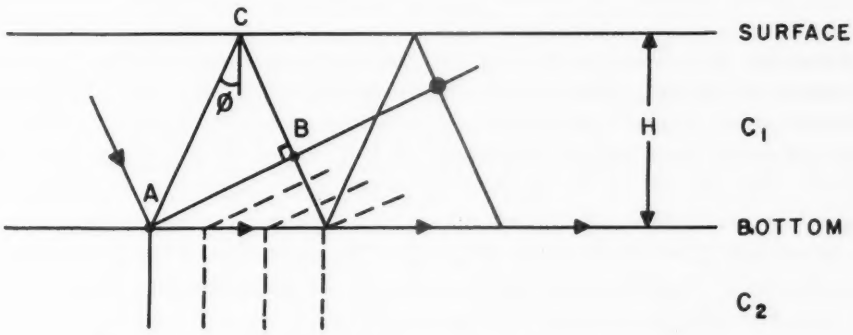

FIG. 5. Interference of refraction waves set up by multiple reflections within water layer of thickness H.

PHYSICAL SIGNIFICANCE OF THE FREQUENCY SELECTIVITY

The refraction arrival at a distant point will have maximum intensity for those frequencies for which there is constructive interference of the refraction waves set up by the multiple reflections from the free surface (see Figure 5.)* This corresponds to a phase difference of 2π between the waves at A and B, or

$$\frac{\omega_0}{c_1}\left[\overline{AC} + \overline{CB}\right] - \pi = 2(n-1)\pi \tag{42}$$

since the reflection coefficient on the bottom is zero at the critical angle, ϕ, and the reflection coefficient at the free surface is π. Then, from the geometry of Figure 5,

$$\frac{\omega_0}{c_1}\left[2H\cos\phi\right] = (2n-1)\pi. \tag{43}$$

Substituting $\phi = \sin^{-1}(c_1/c_2)$ and $f_0 = \omega_0/2\pi$ where f_0 is the frequency in cycles per second, gives

* This is similar to the argument used to describe the physical significance of the normal modes in the water channel (Press and Ewing, 1948 and Officer, 1951).

$$f_0 = \frac{(2n - 1)c_1c_2}{4H\sqrt{c_2^2 - c_1^2}} . \tag{44}$$

We may obtain the same expression from Equation (37):

$$\frac{\omega}{c_1} H \sqrt{1 - \frac{c_1^2}{c_2^2}} = (2n - 1)\frac{\pi}{2} \tag{45}$$

or

$$f_0 = \frac{(2n - 1)c_1c_2}{4H\sqrt{c_2^2 - c_1^2}} . \tag{46}$$

From the above discussion it should be clear why there is a frequency dependence for the refraction arrival in the layered case and not in the single boundary case. In the layered media the refraction is set up from the mutual interference of the multiple reflections at the critical angle in the overlying channel. This occurs at the discrete frequencies, ω_0. The range dependence is spherical, r^{-1} for the velocity potential (r^{-2} for intensity). For the single boundary the refraction is set up from the single critical angle ray; it has no frequency dependence. It is similar to a Lloyd mirror effect and correspondingly falls off as r^{-2} for the velocity potential (r^{-4} for intensity).

REFRACTION ARRIVALS IN MULTIPLE LAYERED MEDIA

In multiple layered media the branch line integral describes the refraction arrival from the lowest horizon. Its solution is exactly equivalent to equation (41). The refraction arrival from the intermediate layers are contained in the normal mode evaluation of the poles. Depending on the thicknesses and physical

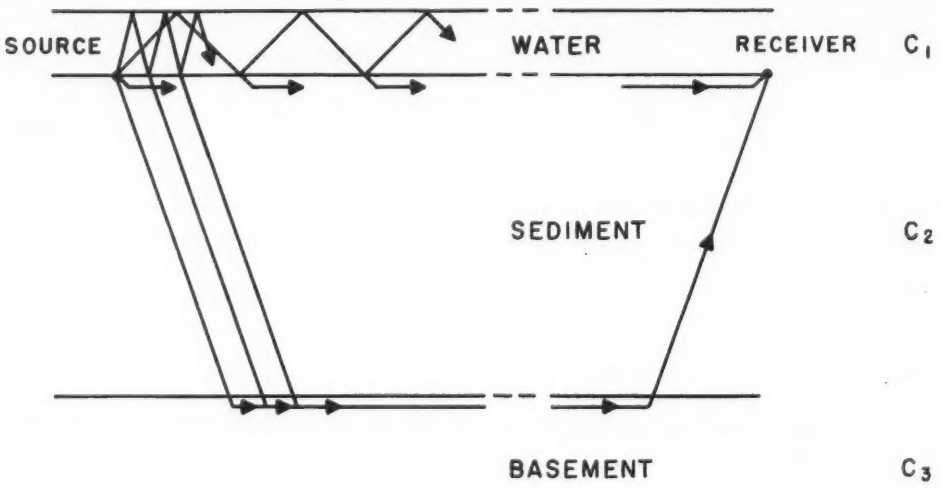

FIG. 6. Refraction over continental shelf areas.

properties of the media, these arrivals may be set up in the manner shown in Figure 5 with the frequency dependence of equation (44), or they may be determined solely by the method of Press and Ewing (1952).

Over the continental shelf areas a relatively simple geologic structure is usually found. It consists of a section of unconsolidated sediment and sometimes semiconsolidated and consolidated sediment down to the crystalline basement. The ratio of thickness of sediment to water is 5:1 or greater. Refractions are obtained from the top of the unconsolidated sediment, one or two intermediate horizons if present, and the basement (see Figure 6). Due to the thickness of the sediment, the ratio of the thickness of sediment to water, and the excess absorption in the sediment, the frequency selectivity for the lower horizon, i.e., the basement, will be determined by the constructive interference of the multiple reflections in the water channel alone. For the same reasons the sediment refraction will be determined by the multiple reflections in the water channel and not from reflections from the basement. Thus, the frequency selectivity for both arrivals will be given by equation (44).

OBSERVATIONS

In order to test the range dependence predicted by equation (41) for the primary refraction arrival, a series of measurements was made in Buzzard's Bay, Massachusetts. One-half pound charges of TNT-tetryl were fired on the bottom at various distances from the receiver, also on the bottom. Two receiving systems were used, both consisting of a Brush Development Co. Type AX-58 hydrophone, an underwater sound amplifier (Dow, 1952), a pen motor driver, and a Sanborn recorder. Both systems were calibrated through the hydrophone at the frequency of the refraction arrival.

If α is the range coefficient for the velocity potential of the refraction arrival, then the average intensity I will be given by

$$I = Ar^{-2\alpha} \tag{47}$$

or, in terms of decibels,

$$10 \log I = 10 \log A - 20\alpha \log r \tag{48}$$

so that a plot of the intensity, expressed in decibels, versus log r should be a straight line with slope 20α. Figure 7 is such a plot for one of the receiving systems. Both gave a value of 1.25 for α. This compares well with the theoretical value of 1.0 from equation (41), especially considering that there would be an increase over the theoretical value from such effects as absorption, scattering in the medium, and rough surface reflection and refraction.*

Table I gives a comparison of the experimentally measured frequencies of

* Perkins (1952) has a plot of log of the relative amplitude of the refraction arrival versus log of the shot-detector distance for a profile made on Bikini Atoll. For the refraction arrival from the igneous basement a value of 1.28 for α can be read from his graph.

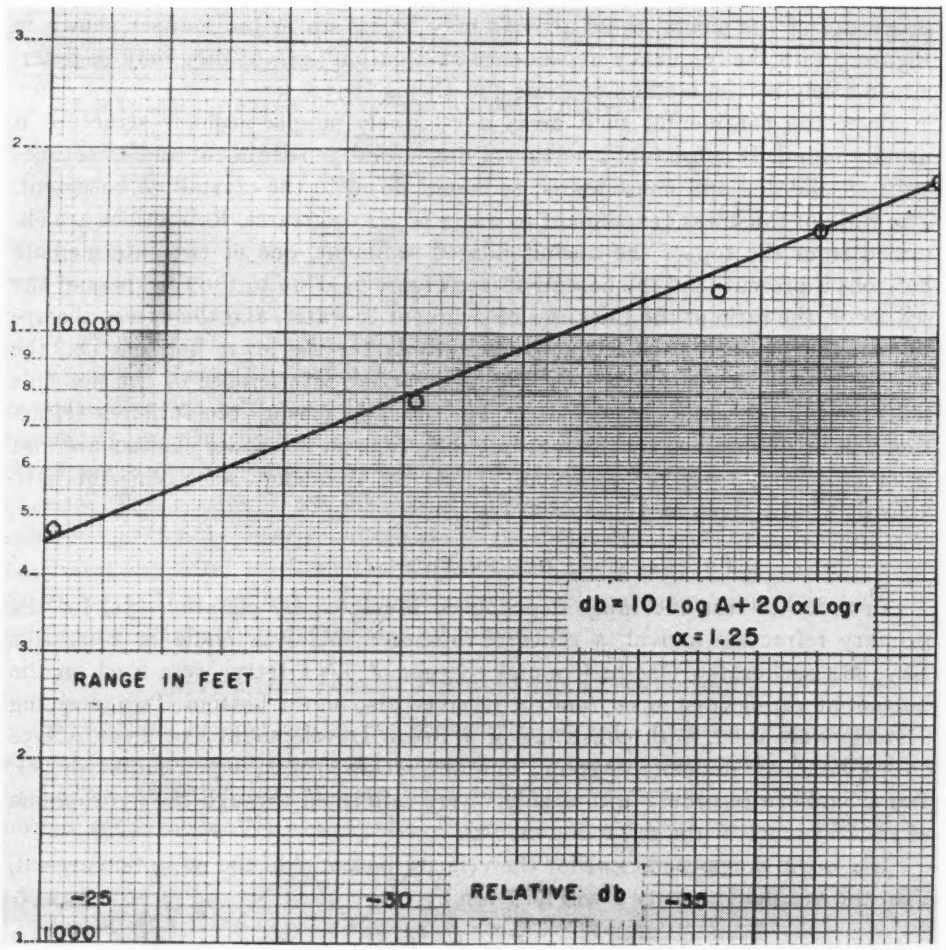

FIG. 7. Refraction arrival intensity vs. range.

the basement and sediment refraction arrivals and those predicted from equation (44) for four profiles made in Buzzard's Bay and on the continental shelf south of Cape Cod. In addition it contains a summary of the refraction results. The frequencies quoted for the experimental data are averaged from all the records for each profile; there is a variation of ± 1–2 cycles per second for a particular mode among the records of a given profile, except for the second mode of the sediment refraction on Profile 1, where the error in reading the frequency of the arrival itself is much larger. The agreement between the theoretical and experimental values is good. Figure 8 is a graph of Equation (44); frequency is plotted against depth of water for various velocity contrasts c_n/c_1 for the first three modes.

The character of the refraction arrival in water covered areas is in agreement

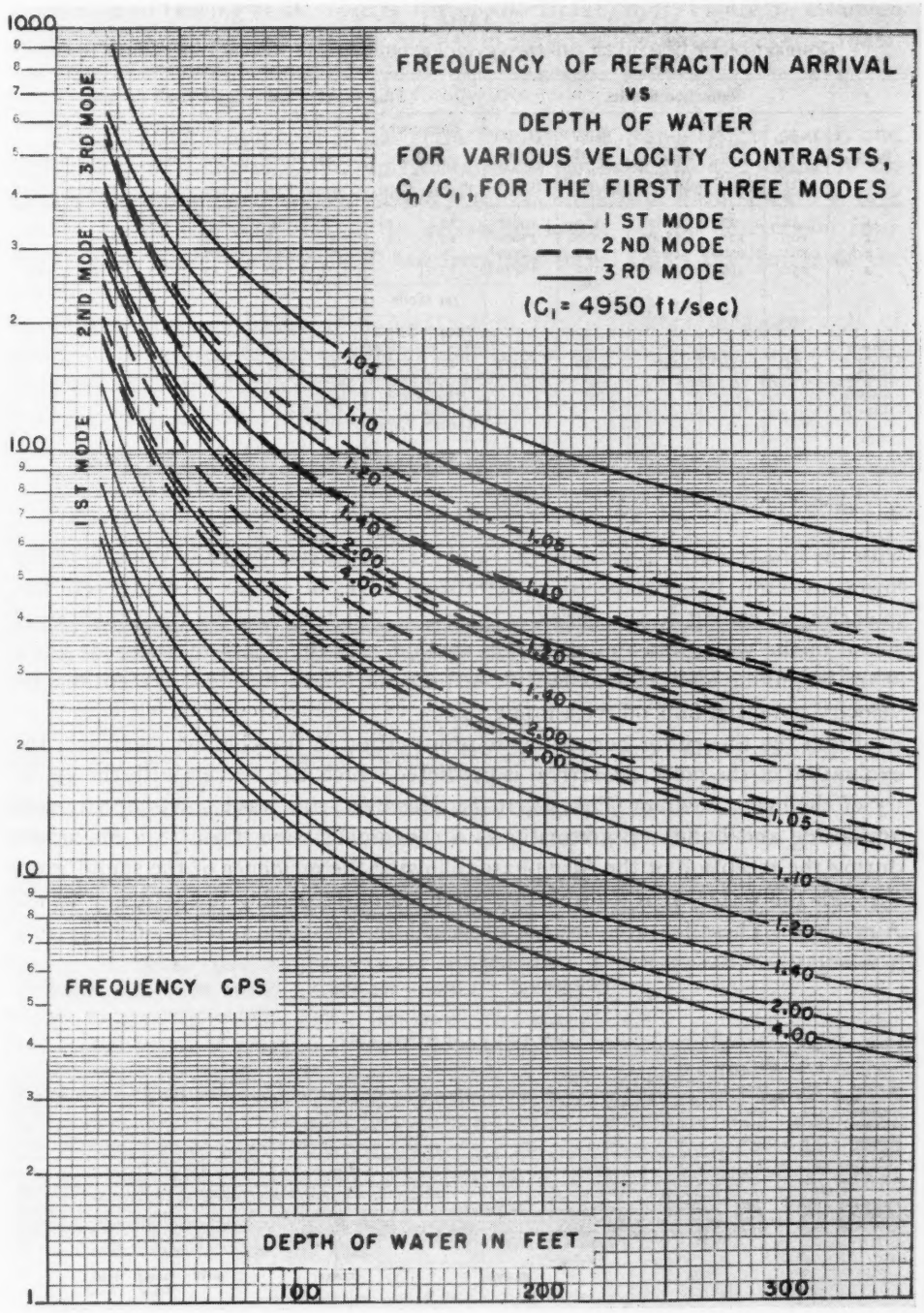

FIG. 8. Chart for determining refraction velocity from frequency of refraction arrival and water depth.

TABLE I

COMPARISON OF COMPUTED AND OBSERVED FREQUENCIES OF REFRACTION ARRIVALS

Refraction Results						Frequencies of Refraction Arrivals (in cps)							
						Basement		Sediment					
						1st Mode		1st Mode		2nd Mode		3rd Mode	
Profile	Depth of Water (ft)	Thickness of Sediment (ft)	Water Velocity (ft/sec)	Sediment Velocity (ft/sec)	Basement Velocity (ft/sec)	Theory	Expt.	Theory	Expt.	Theory	Expt.	Theory	Expt.
1	52	270	4890	5100	19650	26	27	83	83	250	215±		
2	107	1270	4890	5870	17600	12	14	21	21	65	62		
3	162	2200*	4900	5490	19350*			18	18	53	56		
4	252	2690*	4930	6160	18750*			8	9	25	23	41	44
						1st Mode							
						Theory	Expt.						
From Oliver & Drake (1951) (Fig. 9)	75	1500	4950	6490	17425	17	17	25	24	76	75		
						2nd Mode							
						Theory	Expt.						
						52	54						

* Values quoted from Ewing et al. (1950).

with the prediction of Equations (41) and (44). It travels with the velocity of the lower medium. It is composed of a train of waves of one or more discrete frequencies, according to the series, 1, 3, 5, . . . , determined by the velocities of sound in the water and the refraction medium and the depth of water. It has a sharp beginning and stays at fairly constant amplitude during its reception. Its velocity potential falls off with range as r^{-1}.

From the theory for normal mode propagation in the channel itself, i.e., the evaluation of the poles, an arrival is predicted which also travels with the velocity of the lower medium (Pekeris, 1948). However, this wave starts out at zero amplitude and builds up gradually as a continuous wave train to a maximum during the reception of the Airy phase following the incidence of the sound wave through the water. It is a dispersive wave train, decreasing in frequency to the Airy phase. These features are not observed on refraction profiles over the con-

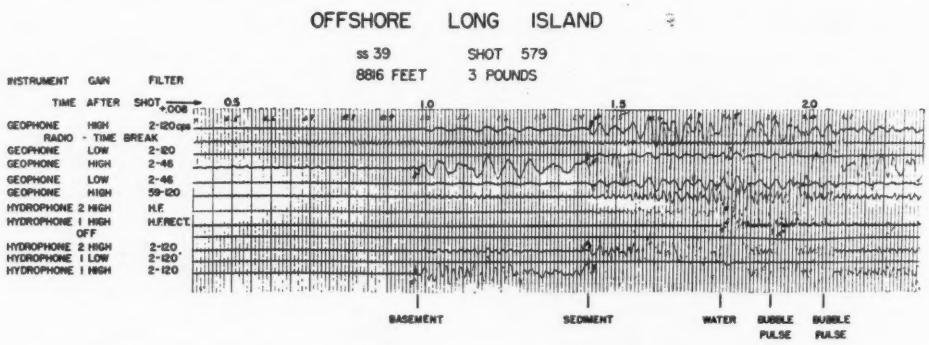

FIG. 9. Sample record showing refraction arrivals recorded at sea off Long Island by Oliver and Drake. Reproduced by permission of Geological Society of America.

tinental shelf (Ewing et al., 1950 or Oliver and Drake, 1951, Figure 9), although they have been observed on some profiles in very shallow water (Pekeris, 1948).

CONCLUSIONS

Knowing the frequencies of the refraction arrivals, the depth of water, and the velocity of sound in water, one can calculate the velocities and depths of the seismic refraction horizons from a single refraction record. From Figure 8, or a similar graph, the velocities of the refraction layers can be determined from the frequencies of the arrivals. Then from the travel times the depths of the horizons can be computed.

This method could be of importance in reconnaissance measurements of geologic structure over the continental shelves or of similar structures on land. In either case knowledge of the frequency of the refraction arrival increases the potential information available on a record.

ACKNOWLEDGMENTS

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A UNIVERSAL SLIDE RULE FOR COMPUTING THE DIPS OF REFLECTING HORIZONS ON THE ASSUMPTION OF LINEAR INCREASE OF VELOCITY*

JOHN DALY†

ABSTRACT

A slide rule is described by which the dip of reflectors can be computed rapidly and accurately for the case where instantaneous velocity can be assumed to increase linearly with depth. Values for initial velocity V_0, rate of increase of velocity, k, and the spread distance Δx, can be introduced into the device easily and changed at will. In conjunction with a previously described instrument, normal move-out graphs and wave front charts can be constructed quickly and precisely.

In almost all areas in which the reflection method is employed, a convenient and accurate means of approximating the velocity distribution is to assume a linear increase of instantaneous velocity with depth. This is expressed by the equation:

$$V_z = V_0 + kz \tag{1}$$

where V_0 is the surface or sub-weathering velocity, V_z is the instantaneous velocity at depth z and k is a constant of proportionality. Both V_0 and k may have different values in different localities.

This type of velocity distribution defines a series of circular wave fronts and trajectories, charts of which offer a precise solution to the geometrical problems encountered in reflection seismograph work. The angle of dip α, can be read from suitable $t_1-\Delta t_1-\alpha$ graphs, when t, the observed reflection time and Δt, the step-out time, are known. Whenever the values of V_0 or k change, it is necessary to construct new charts and graphs. Changes in the $t_1-\Delta t_1-\alpha$ graphs are also necessitated whenever the spread distance is changed.

The construction of new charts and graphs is laborious, expensive and time consuming. An instrument for plotting reflection data which overcomes these difficulties has already been described (Daly, 1948). A companion device, a slide rule for computing the dip of the reflectors, is introduced in this paper. This slide rule obviates the necessity of using $t_1-\Delta t_1-\alpha$ graphs and is so designed that errors in reading are minimized. It has been used since 1938 and has proven of great value and practicability.

An equation familiar in the seismic literature (used frequently, but originally published by Ewing and Leet, 1932) for normal incidence

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$$e^{kt/2} = \frac{\tan \frac{\alpha}{2}}{\tan \frac{\alpha_0}{2}}$$

may be expressed in the form:

$$\frac{\sin \alpha_0}{1 + \cos \alpha_0} = \frac{\tan \frac{\alpha}{2}}{e^{kt/2}} \tag{2}$$

where t = observed reflection time at the shot point, k = rate of velocity increase, α = angle of dip of the reflecting horizon, and α_0 = angle of emergence.
Now

$$\sin \alpha_0 = \frac{V_0 \Delta t}{\Delta x}$$

where

V_0 = initial velocity,

Δt = observed time difference at the ends of the spread,

and

Δx = spread distance.

We can write

$$\frac{\sin \alpha_0}{1 + \cos \alpha_0} = \frac{\frac{V_0 \Delta t}{\Delta x}}{1 + \sqrt{1 - (V_0 \Delta t / \Delta x)^2}} = \frac{V_0 \Delta t}{\Delta x + \sqrt{\Delta x^2 - (V_0 \Delta t)^2}}. \tag{3}$$

Substituting (3) in (2) and transposing,

$$\frac{\Delta x + \sqrt{\Delta x^2 - (V_0 \Delta t)^2}}{V_0 \Delta t} = \frac{e^{kt/2}}{\tan \frac{\alpha}{2}}. \tag{4}$$

Also,

$$\ln \frac{\Delta x + \sqrt{\Delta x^2 - (V_0 \Delta t)^2}}{V_0 \Delta t} = \cosh^{-1} \frac{\Delta x}{V_0 \Delta t}. \tag{5}$$

Substituting (5) in (4) and transposing:

$$\ln \tan \frac{\alpha}{2} = \frac{kt}{2} - \cosh^{-1} \frac{\Delta x}{V_0 \Delta t}. \tag{6}$$

The above equation can be solved by a slide rule.

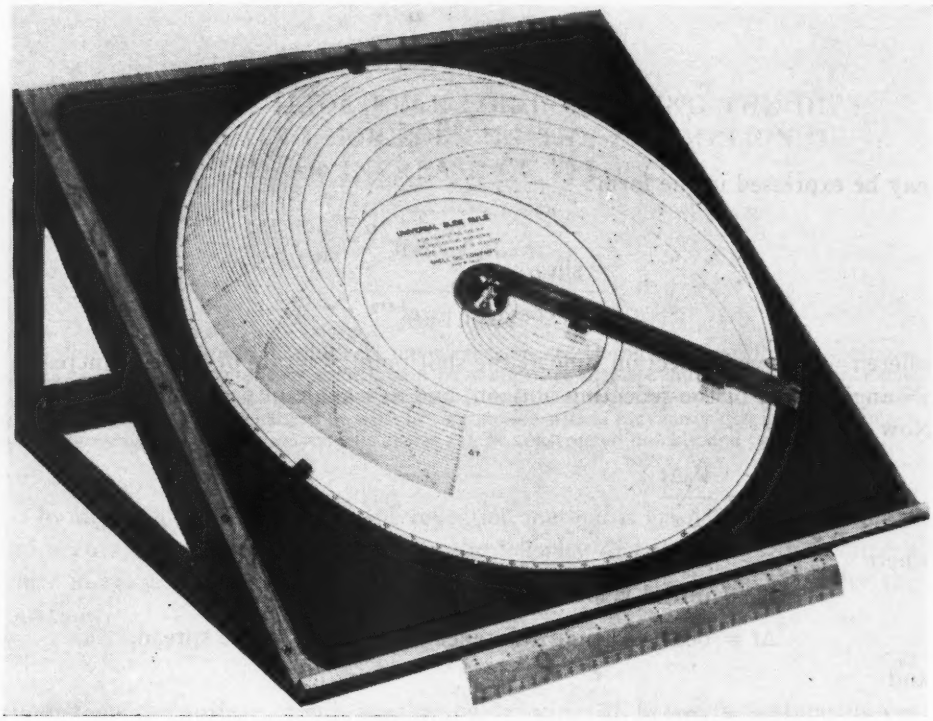

FIG. 1. The circular slide rule.

The first slide rule to be built was circular (see Fig. 1). The model now used by the writer is straight (see Fig. 2) and it is this one that is described in the present paper. These instruments do not differ in principle, only in shape.

On the lower scale, constant t values are plotted as continuous curves from values of $k=0.0$ to $k=1.16$. On the center scale, which is movable, $\cosh^{-1}\Delta x/V_0\Delta t$ is plotted for values of Δt from 0.001 to 0.70 plotted against a vertical logarithmic scale. The third, or upper, scale, which is also on the movable slide, is a graph of $\ln \tan(\alpha/2)$ expressed in values of α from $\frac{1}{4}$ degree to 140 degrees. The curves are reproduced on photographic paper and cemented on the wood frame.

The device is provided with a movable, transparent cross-arm which is equipped with two adjustable reading targets. One target can be set over the t scale for any given value of k. The other is attached to an adjustable logarithmic scale with values of V_0 from 2,200 ft/sec to 23,000 ft/sec. This moves along another logarithmic scale showing values of Δx from 200 ft to 10,000 ft. When the scale bearing the target is set so that the given values of V_0 and Δx coincide, the cross hairs of the target are set for the proper ratio of $\Delta x/V_0$.

In use the cross hairs are set to conform to the constants Δx, V_0 and k. The cross arm is moved so that the lower reading target is set at the observed reflection time t. The middle scale is moved to the left until the observed Δt value is in place beneath the cross hairs of the upper reading window, then the angle of

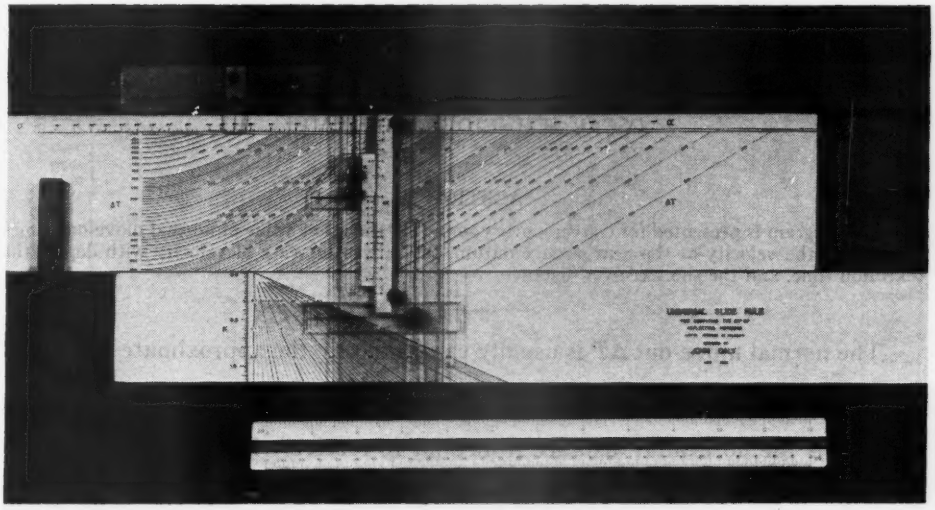

FIG. 2. The straight slide rule.

dip is read off the upper scale at the pointer attached to the upper left portion of the rule.

Experience has shown that computation with this slide rule is very fast and very accurate because the chance for personal error is reduced to a minimum. The principle of the slide rule is adaptable to many of the computations in seismic work and should be used more frequently. For example, a similar rule can be constructed for determining the horizontal offset ξ due to migration, from the equation

$$\xi = \frac{V_0}{k} \sinh \frac{kt}{2} \sin \alpha. \tag{7}$$

The dip slide rule can be used with the previously described plotting instrument (Daly, 1948) to construct wave front charts and normal move-out graphs with less trouble and expense than with conventional methods.

ACKNOWLEDGMENTS

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NOMOGRAM FOR COMPUTATION OF EXACT VALUES OF NORMAL MOVE-OUT TIMES*

OSCAR SCHNEIDER-RIQUELME†

ABSTRACT

A nomogram is presented for conveniently computing the exact value of normal move-out times in terms of the velocity at the near surface datum, the rate of increase of velocity with depth, the reflection time, and the shot-receiver distance.

The normal move-out ΔT is usually calculated by the approximate formula:

$$\Delta T = [ax^2/2V_0^2]/[\exp(aT_0) - 1] \tag{1}$$

where x is the horizontal distance from shot to receiver, V_0 is initial velocity at the datum surface, a is rate of increase of velocity with depth and T_0 is the time from the datum at the shot point to the reflector and return. This formula is not accurate enough for large values of ΔT and small values of T_0.

C. H. Dix (see Mansfield, 1947) has deduced the following equation which permits the calculation of the exact value of the normal move-out:

$$\coth p(\cosh q - 1) + \sinh q = r_0 \tag{2}$$

where

$$p = aT_0/2, \qquad q = a\Delta T/2, \qquad r_0 = a(\Delta T)_0/2,$$

$(\Delta T)_0$ being the approximate normal move-out obtained by the use of Equation (1).

In explicit form, q is given by:

$$q = -p + \cosh^{-1}[(r_0 + \coth p)\sinh p]. \tag{3}$$

This formula looks simple, but in practice it is too cumbersome to use. Fortunately it is possible to prepare a nomogram of aligned points giving the value of q as a function of p and r_0.

Writing equation (2) as a determinant we obtain:

$$\begin{vmatrix} -\coth p & 1 & 1 \\ \tanh q & (\cosh q - 1)/\cosh q & 1 \\ r_0 & 0 & 1 \end{vmatrix} = 0 \tag{4}$$

This determinant (Allcock and Jones, 1941, pp. 23–33) is the "characteristic determinant" of a nomogram of aligned points representing graphically equation (2). The first column gives the ordinates of the scales of the variables p, q, and r_0;

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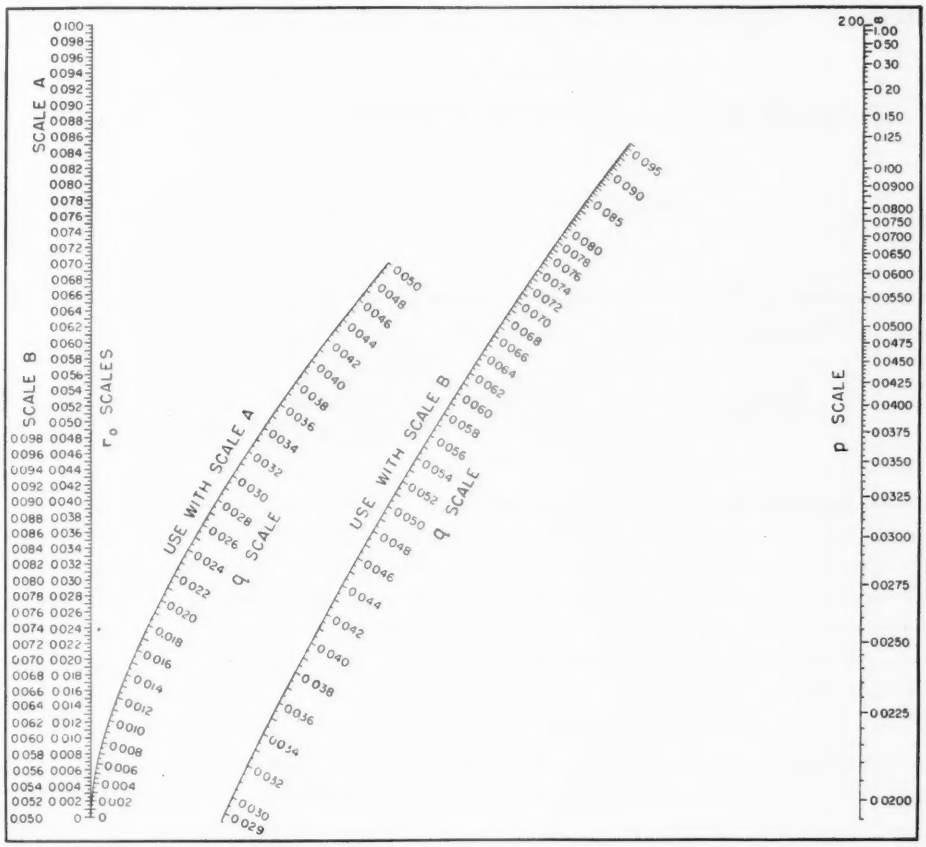

FIG. 1. Nomogram for computation of exact values of normal move-out times.

the second column gives the corresponding abscissas in any plane cartesian system of coordinates.

The ranges selected for the variables are:

$$0.020 \leqq p \leqq \infty$$

$$0 \leqq r_0 \leqq 0.100$$

In order to plot these ranges properly, the nomogram given by the determinant (4) must be modified. This has been done by multiplying determinant (4) by non-null determinants (Allcock and Jones, 1941, pp. 107–110). The following multiplication rule has been used:

$$\begin{vmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{vmatrix} \times \begin{vmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{vmatrix} = \begin{vmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & c_{33} \end{vmatrix}$$

where:

$$c_{ij} = \sum a_{ik} \times b_{kj}; \qquad k = 1, 2, 3.$$

Multiplying determinant (4) by the determinant

$$\begin{vmatrix} 400 & 0 & 0 \\ 20.4 \times 10^3 & 20 \times 10^3 & 998 \\ 0 & 0 & 2 \end{vmatrix} \neq 0$$

and dividing each row of the resulting determinant by the corresponding term of the third column we obtain:

$$\begin{vmatrix} -0.4 \coth p + 20.4 & 20 & 1 \\ 20 \dfrac{20 \sinh q + 1.02 \times 10^3 (\cosh q - 1)}{10^3 (\cosh q - 1) + 2} & 20 \dfrac{10^3 (\cosh q - 1)}{10^3 (\cosh q - 1) + 2} & 1 \\ 200 r_0 & 0 & 1 \end{vmatrix} = 0. \qquad (5)$$

In the same way, using the determinant

$$\begin{vmatrix} 400 & 0 & 0 \\ 20.42 \times 10^3 & 20 \times 10^3 & 998 \\ -20 & 0 & 2 \end{vmatrix} \neq 0$$

one obtains:

$$\begin{vmatrix} -0.4 \coth p + 20.4 & 20 & 1 \\ 20 \dfrac{20 \sinh q + 1.02 \times 10^3 (\cosh q - 1) - \cosh q}{10^3 (\cosh q - 1) + 2} & 20 \dfrac{10^3 (\cosh q - 1)}{10^3 (\cosh q - 1) + 2} & 1 \\ 200 r_0 - 10 & 0 & 1 \end{vmatrix} = 0. \qquad (6)$$

Determinants (5) and (6) have been converted into the accompanying nomogram (Figure 1). The scales have been plotted using an orthogonal system of coordinates and 0.74 centimeters as the unit of distance.

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PROBLEM AREAS FOR THE SEISMOLOGIST*

GLENN M. CONKLIN†

ABSTRACT

This paper describes interpretative problems encountered in four widely scattered areas: Southern Florida; Beaver County, Oklahoma; the Plainview Basin of the Texas Panhandle; and Hancock County, Mississippi.

Secondary refraction recordings offer problems, because refractions from deep beds are distorted and obscured by energy from shallow beds. The energy associated with the shallow refractors appears as multiples and is sustained for long periods of time. In Beaver County, Oklahoma, extreme variations in velocity cause distortion of reflections and introduce apparent dips which are erroneous. This velocity variation is thought to be due to differential salt solution from the Blaine-Cimarron interval. In the Plainview Basin of the Texas Panhandle and in Hancock County, Mississippi, multiple reflections are troublesome. These reflections are discussed and records and cross-sections illustrate these events. Some suggestions for the treatment of these problems are advanced.

In the interpretation of seismic records it is assumed usually that data obtained from good records give reliable maps and likewise that poor data produce unreliable maps. These two assumptions may not be true because the so-called good data may be good in appearance only and the poor-appearing data may be more reliable. The purpose of this discussion is to point out instances when data, apparently quite good, must be used with extreme caution to avoid erroneous interpretations.

Examples of problems in the choice of data will be drawn from four areas, widely scattered geographically and quite different geologically. Some of these problems may be classed in the nuisance category and may be only time-consuming and expensive. Others, however, are very serious in that unreliable maps can result.

Figure 1 shows a map on which the four areas to be discussed are indicated by arrows.

SOUTHERN FLORIDA

The first area to be considered is southern Florida, a basin having a considerable and undetermined thickness of sediments which, for the most part, are carbonate in nature. Oil is produced commercially in only one field—Sunniland—operated by the Humble Oil and Refining Company. Production is from the Sunniland Lime, Lower Cretaceous in age, at a depth of about 11,500 feet. Since shows of oil have been encountered in all deep wells south of Tampa, this basin is considered quite promising for additional production.

Much of the limestone is vuggy, with high porosity and little or no permeability. The exploration problem is two-fold: first, to locate a structure; second, to find rocks that are sufficiently permeable to allow movement of oil.

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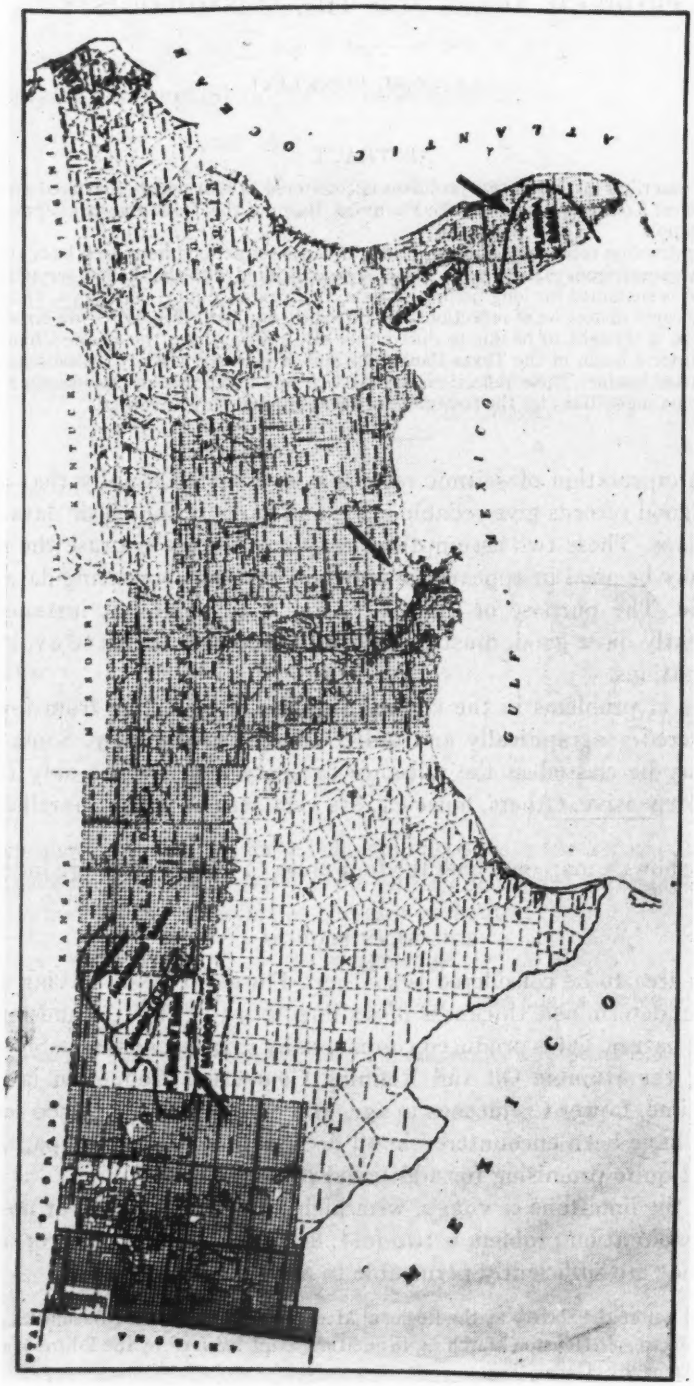

FIG. 1. Map showing location of problem areas discussed in this paper.

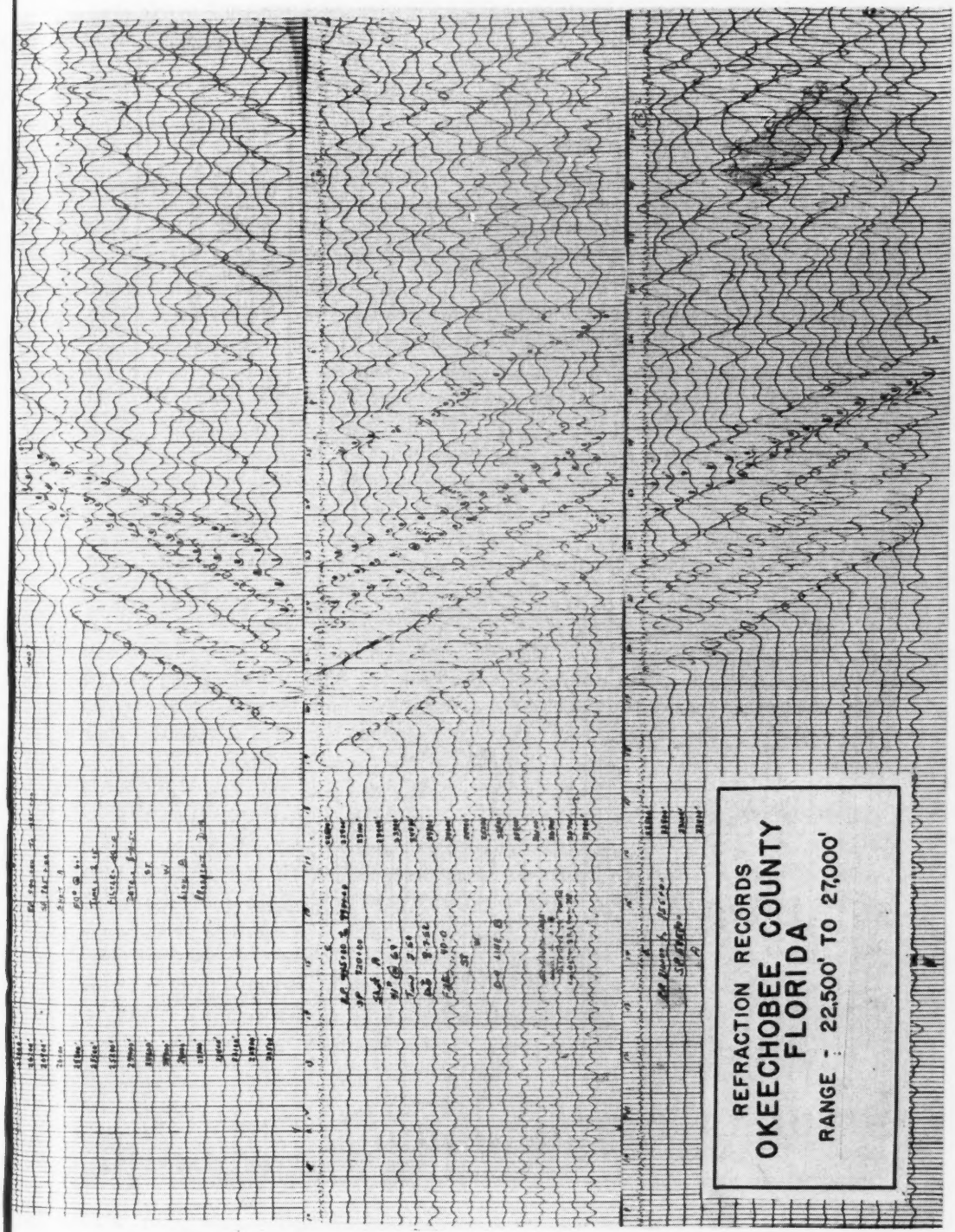

FIG. 2. Good refraction records showing discrete arrivals from 16,000 ft/sec and 20,000 ft/sec horizons.

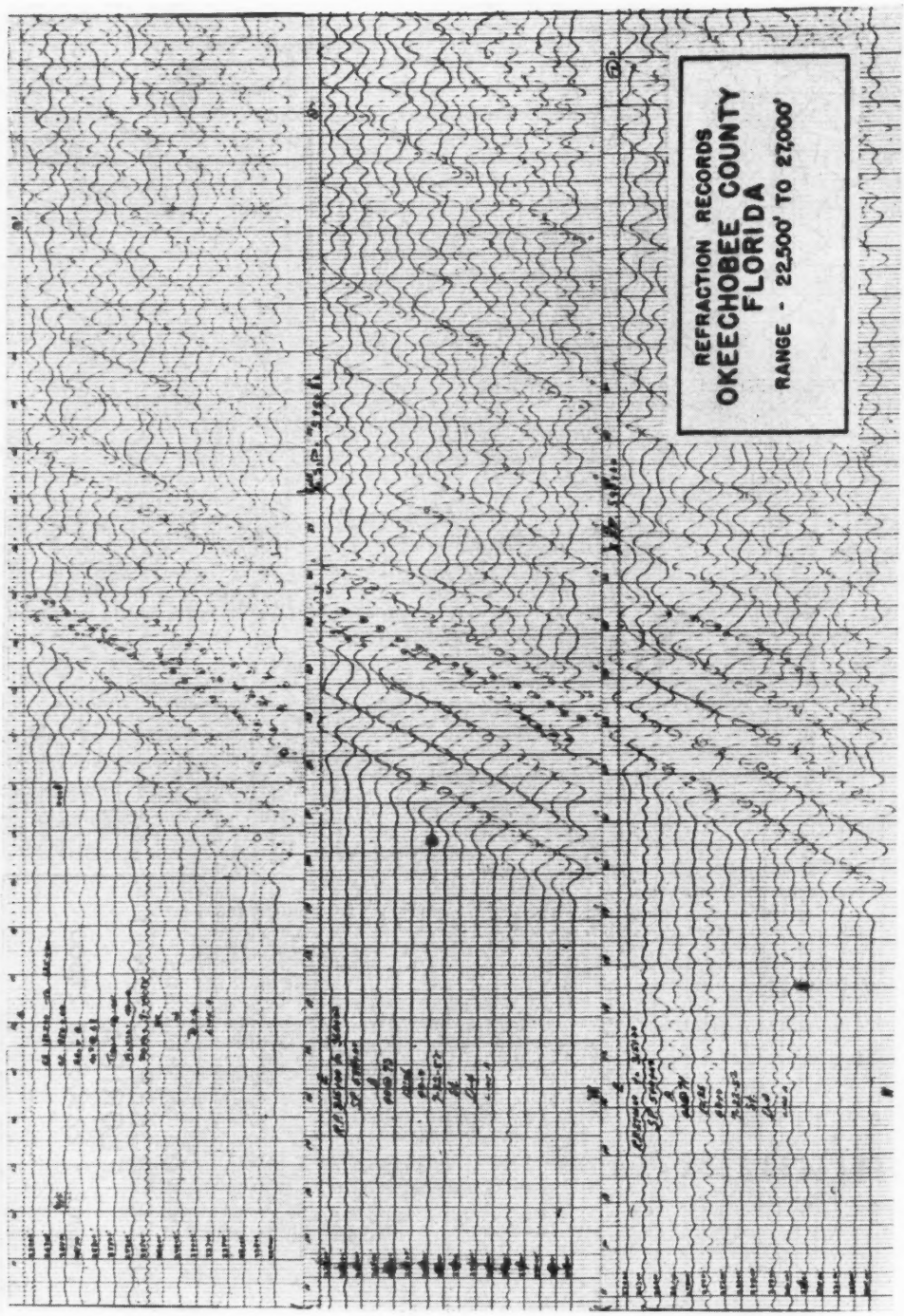

FIG. 3. Refraction records showing how a high velocity arrival can be masked by multiples of any earlier low-velocity arrival.

Reflection mapping has been tried using the usual variations of instruments, holes, and spreads. In general the reflection method appears to be unsatisfactory, or at least disappointing. There are numerous reasons for the poor quality of reflections. One is the sand which covers a large part of the surface; another is the predominance of lime and other carbonate rocks in the section. There seems to be a marked absence of the well-defined velocity and density contrasts which are considered necessary for successful reflection work.

Although reflection shooting appears unsatisfactory generally, the refraction method may be useful in certain areas in mapping the Upper Cretaceous and possibly the Lower Cretaceous. Best results are obtained from relatively small charges in shallow holes.

The refraction records to be discussed were obtained in Okeechobee County. The instrument system used for this work consisted of ordinary reflection amplifiers and low-frequency detectors. The spread distance for the most part was from 22,500 to 27,000 feet. The spread was composed of 16 detectors spaced 300 feet apart. About 40 pounds of explosive at a depth of 50 feet was generally sufficient.

Figure 2 shows some of the better records. The first arrival has an apparent average velocity of about 16,000 feet per second and is refracted from a depth of approximately 3,800 feet. The later event has an apparent average velocity of about 20,000 feet per second and is refracted from a depth of about 10,000 feet. These records are better than average and illustrate that both shallow and deep refractions can be obtained from one shot.

If all the records were as good as this group, there would be no problem for the interpreter. It is apparent, however, on Figure 3 that at some locations unwanted energy is distorting the deep refractions. This high-amplitude, low-velocity energy is recurrent, and each cycle has the same apparent velocity as the first arrival which is from the shallow refractor. These events appear to represent multiple refractions of energy reflected back to the refracting bed from interfaces above.

The deep high-velocity refraction is weaker than the low-velocity multiples. Since this deeper event is superimposed upon the low-velocity multiples, it is obvious there will be difficulty in identifying arrivals from the deep horizon. In order to map the deep horizon, it is necessary to plot all the refraction data in the vicinity of the arrival time for the high velocity refraction. Then these data must be studied carefully for variations in apparent velocities which might be used for identification.

Figure 4 shows records on which interfering multiples are present along with possible fragments of high-velocity events. The problem of securing deep data is well illustrated by this figure.

Fig. 3. Refraction records showing how a high velocity arrival can be masked by multiples of any earlier low-velocity arrival.

BEAVER COUNTY, OKLAHOMA

The second area is in the western part of the Anadarko Basin in Beaver County, Oklahoma. The terrain is relatively flat except for a low-relief drainage

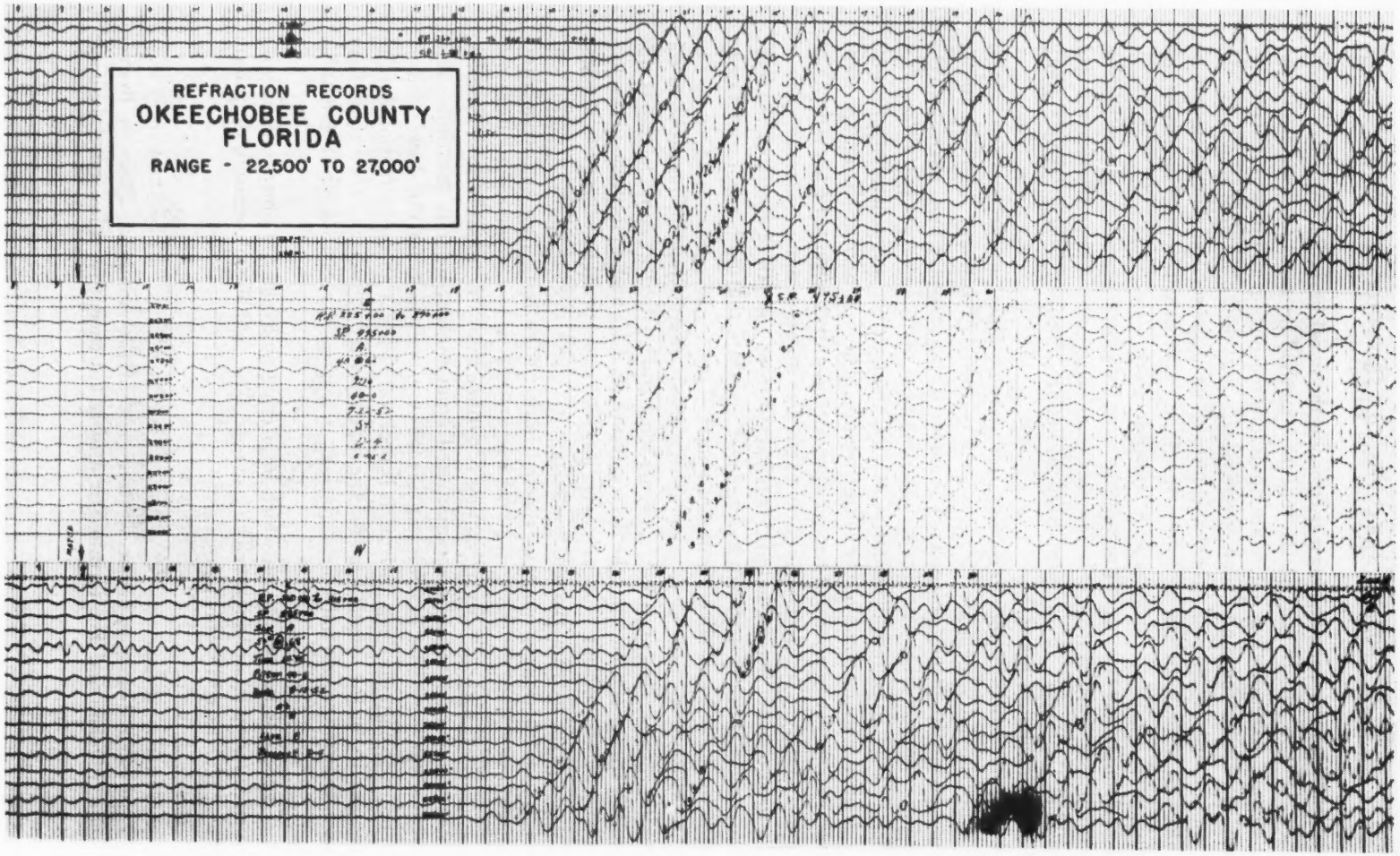

FIG. 4. Interference between high and low-velocity arrivals, with fragments of high-velocity events still observable.

pattern. Caliche is present near the surface in varying amounts and in various degrees of hardness.

In some parts of the area the seismic records are good; however, reflections appear to be distorted by velocity variations in the near-surface beds. This variation is presumed to be caused by a variation in the amount of salt in the interval between the Blaine and the Cimarron in the upper Permian. This interval, of approximately 900 feet, varies as much as 400 feet in some instances. The thinning of section could be due to the solution of salt by ground waters with a resultant slumping of the beds in this interval.

Widess (1952) has discussed variations in velocity as related to the solution of salt by ground waters. The information he presents on this subject leaves little doubt that such a condition exists in this area and that the changes in the velocity in these intervals are due to salt solution.

The salt is interbedded with shales, sands, and anhydrite, and probably contaminates most of the beds in the interval. Some salt is logged below the Cimarron, but the amount is small and solution is not important.

Figure 5 shows three records shot in Beaver County using 1,320 foot split spreads with eight detectors per trace and no other mix or compositing. These records have normal reflection move-out and continuity. This group represents a west-east profile with the top record farthest west.

Figure 6 shows three records which are an eastward continuation of the previous group. The apparent dip across these records is about 350 feet. It is thought that this anomaly is due to a velocity change resulting from salt solution. It is estimated that this effect could result from the removal of between 250 and 300 feet of salt.

Figure 7 shows another group of records which exhibit strong apparent dip of the same kind. Other locations in the area give reflections of the same type with varying degrees of distortion.

There seems to be no positive way in which to determine whether the move-outs are due to dip or variation in the salt content. Some attempts have been made to clarify the interpretation. These include delta-T studies, measurement of interval times between horizons, and velocity profiles, as well as studies in uphole times and weathering thickness.

PLAINVIEW BASIN

Another area in which serious interpretative problems exist is the Plainview Basin of the Panhandle of Texas. This area includes all or part of Lamb, Hale, Bailey, Parmer, Castro, Swisher, Deaf Smith, and Randall Counties, Texas.

The geologic section for the approximate center of this area at the Sun #1 Herring dry hole is as follows: The first 5,500 feet is composed of shale, salt, anhydrite, and dolomite in varying thicknesses and degrees of purity. From 5,500 feet to 7,100 feet (the base of the Permian) the section is dolomitic with a few thin shales and sands. Below 7,100 feet is a shale section about 300 feet thick

FIG. 4. Interference between high and low-velocity arrivals, with fragments of high-velocity events still observable.

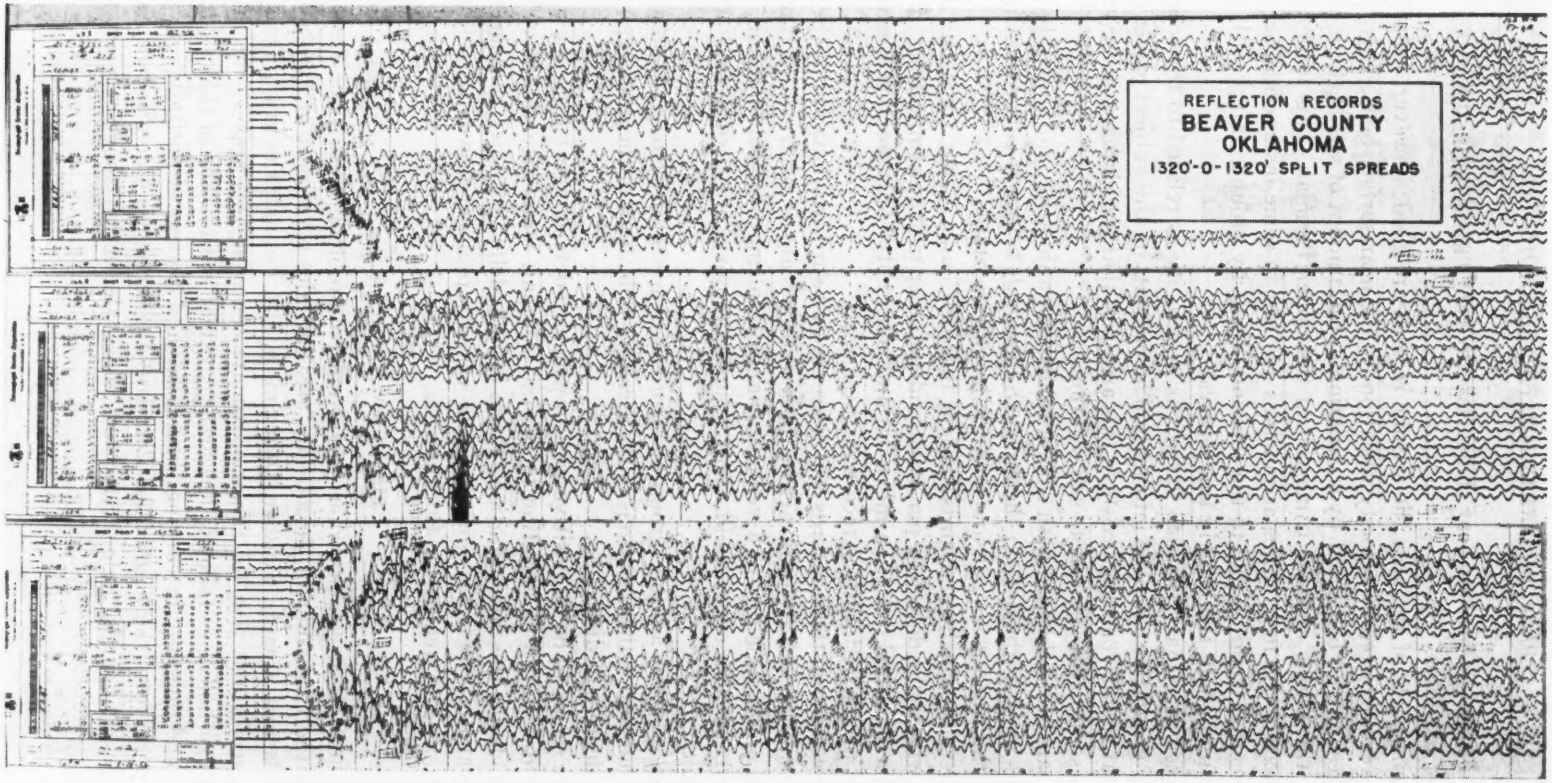

FIG. 5. Correlated group of reflection records from Beaver County, Oklahoma showing normal reflection move-out and continuity.

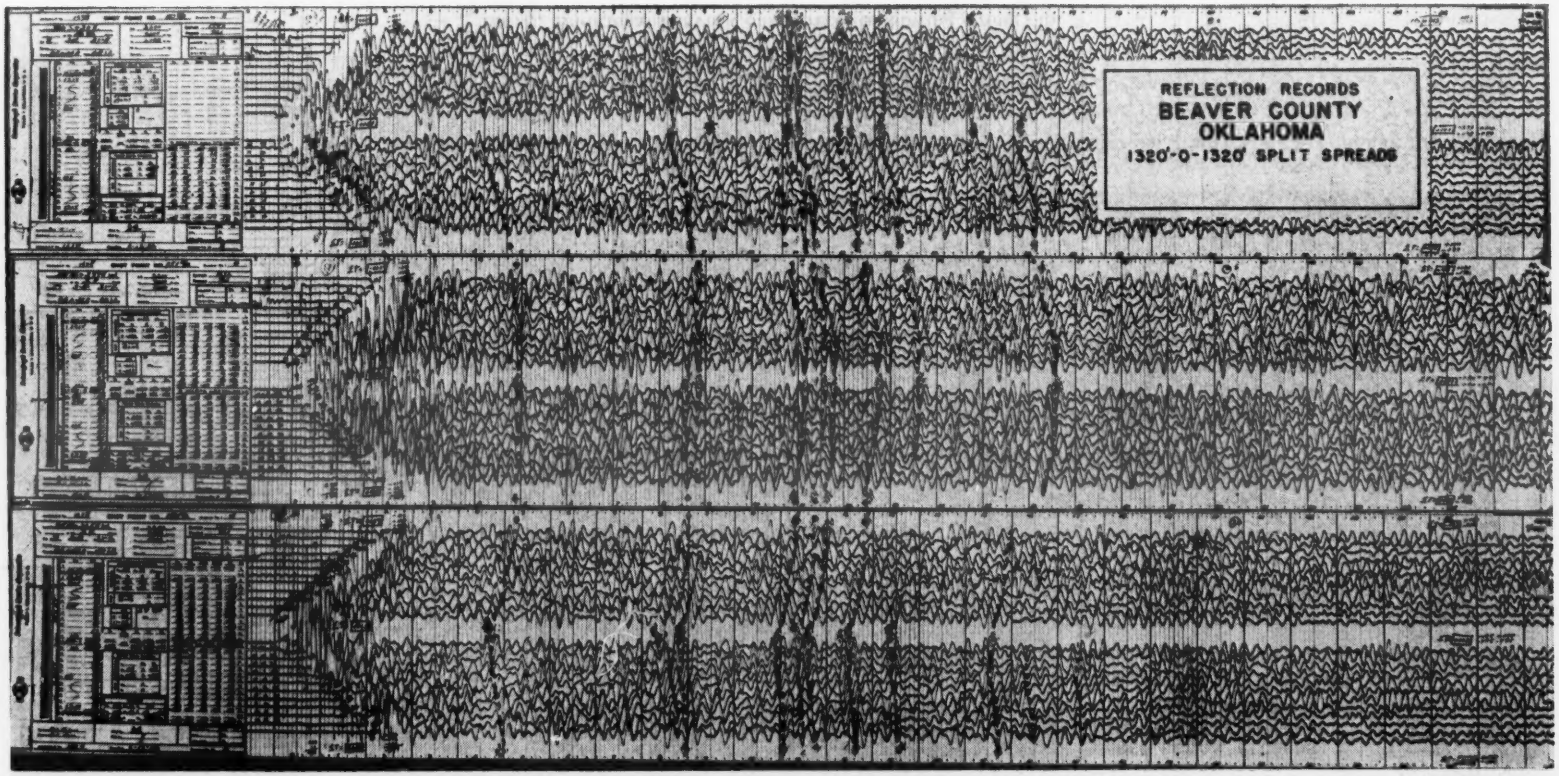

FIG. 6. Reflection records from Beaver County showing abnormal dip attributable to salt solution.

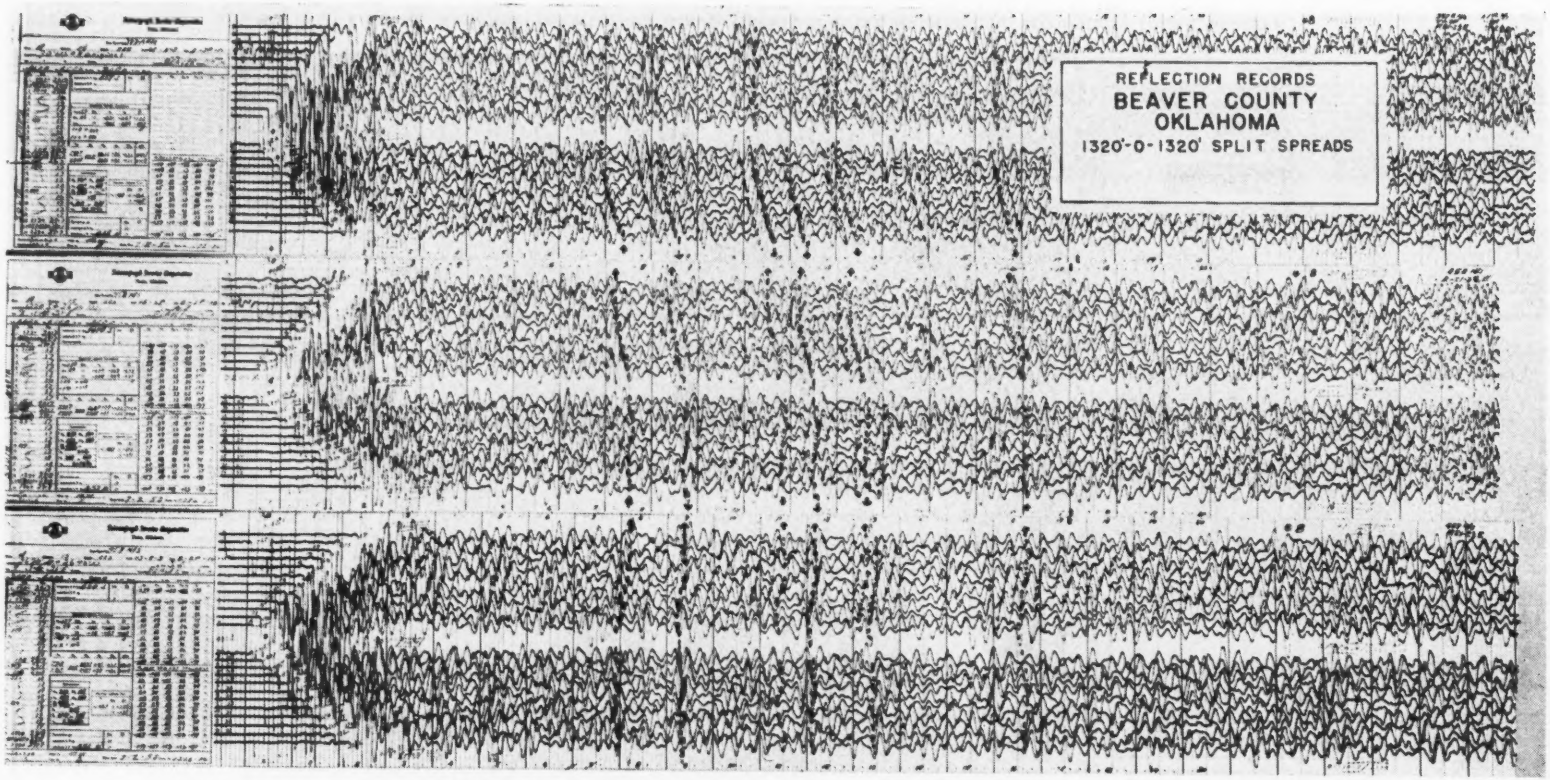

FIG. 7. Additional Beaver County records showing strong dip.

underlain by about 3,000 feet of interspersed limestone, chert, and granite wash. The basement is composed of igneous material (olivine gabbro) in place at 10,400 feet.

This section has several well-defined velocity discontinuities with which reflections are identified. These extend down to the thick dolomite in the lower Permian. Many reflections appear on the records at times which represent depths below the Permian; these events are thought to be multiples of earlier reflections.

Figure 8 shows a record section on which many reflections are present, both before and after the time (1.3 seconds) corresponding to a reflection from the basement. It is not difficult to assume intervals for some of these multiples and to identify many of the reflections as second, third, and possibly fourth multiples.

In this area we had no difficulty tying loops or polygons with wells if we used reflections occurring earlier than one second. After a time of one second, the reflections, although they were continuous for various distances, yielded data that could not be used for mapping with any confidence.

Records in Figure 9 are from an area in which too many reflections are present. The problem, naturally, is to try to separate the primary events from the multiples. Several techniques were tried for getting deep reflections without the multiples. Smaller charges produced fewer multiples but did not eliminate them. Multiples were also observed from experimental air shooting.

A special reflection profile was shot for the purpose of determining the vertical velocity distribution by analytical means. The results of this profile checked the well velocity down to the lower Permian, where the average vertical velocity is about 12,000 feet per second. Reflections on the velocity profiles having arrival times greater than one second still showed velocities of 12,000 feet per second. This was true of events with arrival times of as much as six seconds.

Although the velocity profile will help to identify the various reflections, it will not separate the primary reflections from the multiples. Apparently, the large amount of salt and dolomite limits the penetration of energy to deeper reflectors and may re-reflect downward any energy which might be returning to the surface from the deeper beds. There is no doubt that the amount of energy received at the detectors from deep horizons is so small in comparison to the energy of the multiples that its recognition is difficult or impossible.

HANCOCK COUNTY, MISSISSIPPI

Another troublesome area in an entirely different geological province is the Gulf coastal plain of Hancock County, Mississippi. In this area there are no problems in interpreting reflections from the "Het" or earlier events. At later times, however, multiple events give considerable trouble.

Figure 10 shows some typical records from this area. It is evident that the "Het" reflection is outstanding, and the first multiple of the "Het" is obvious. How many more complicated multiples are present has not yet been determined.

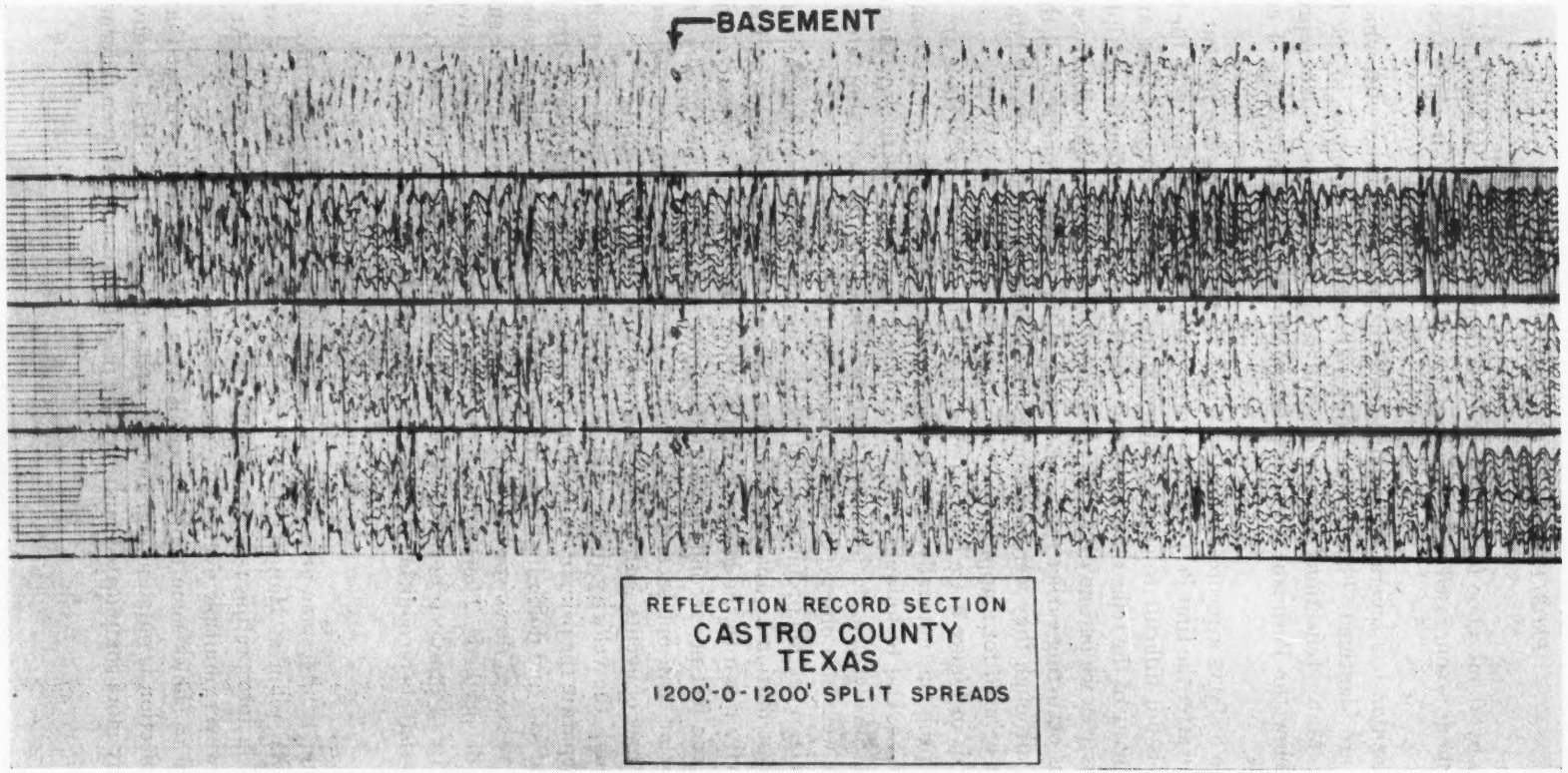

FIG. 8. Records showing reflections which apparently originate below the basement. These are probably multiples.

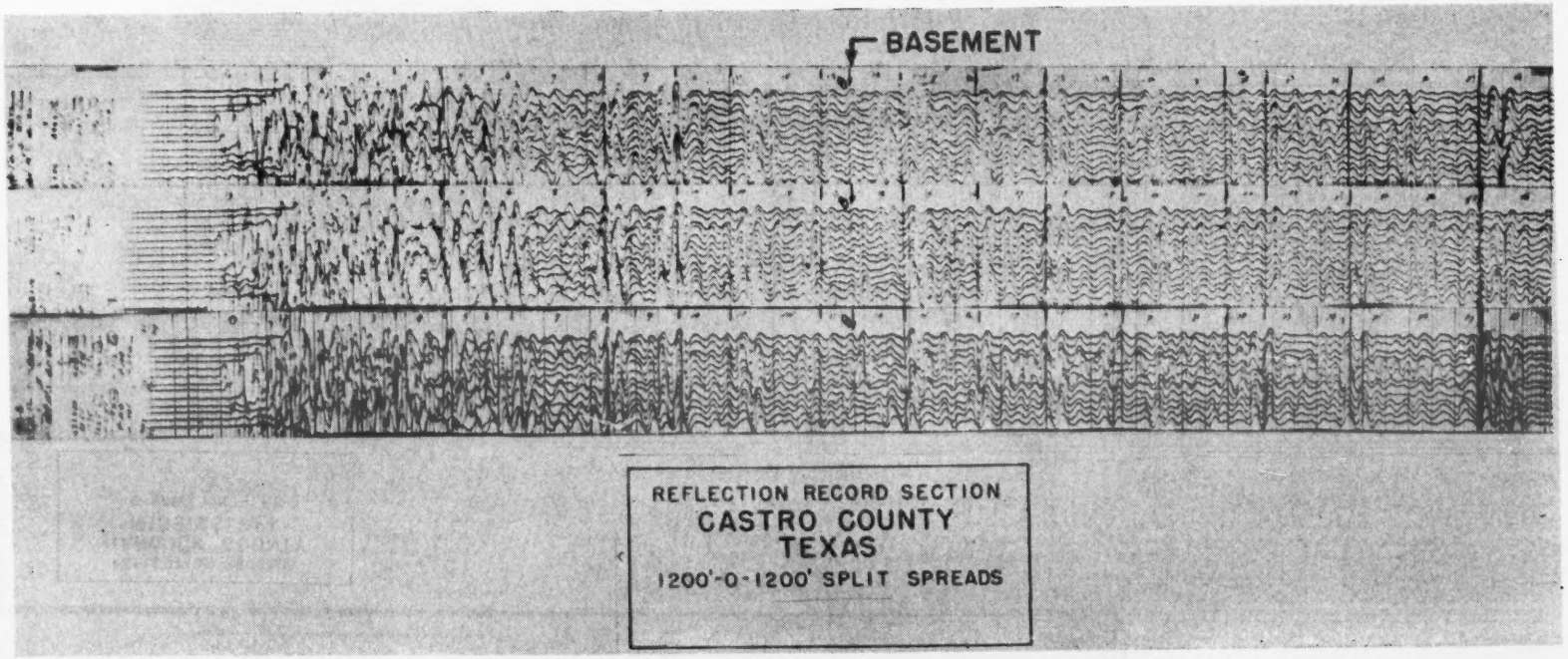

FIG. 9. Additional records showing reflections from below basement.

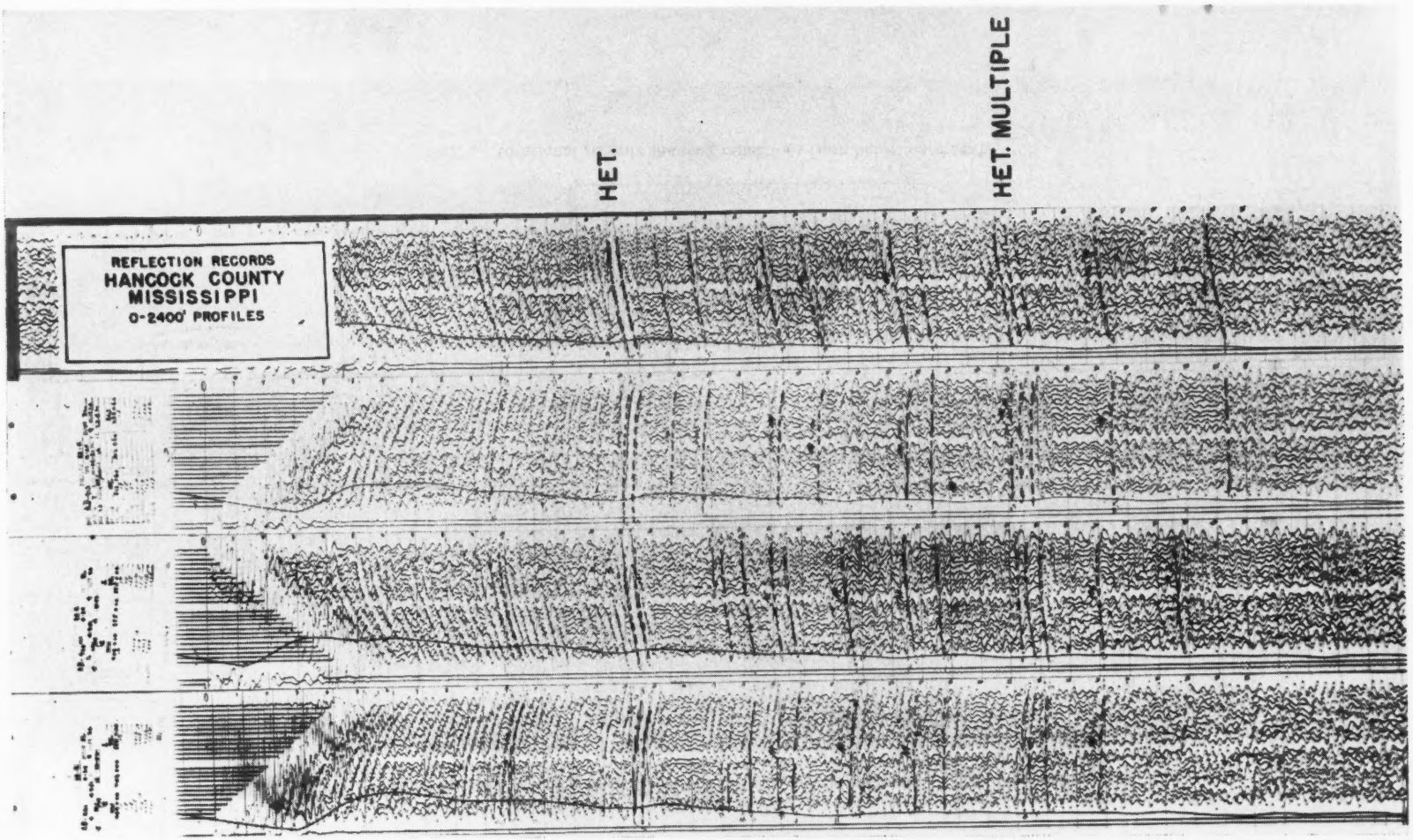

FIG. 10. Typical records from Mississippi showing strong multiple reflection from the "Het."

FIG. 10. Typical records from Mississippi showing strong multiple reflection from the "Het."

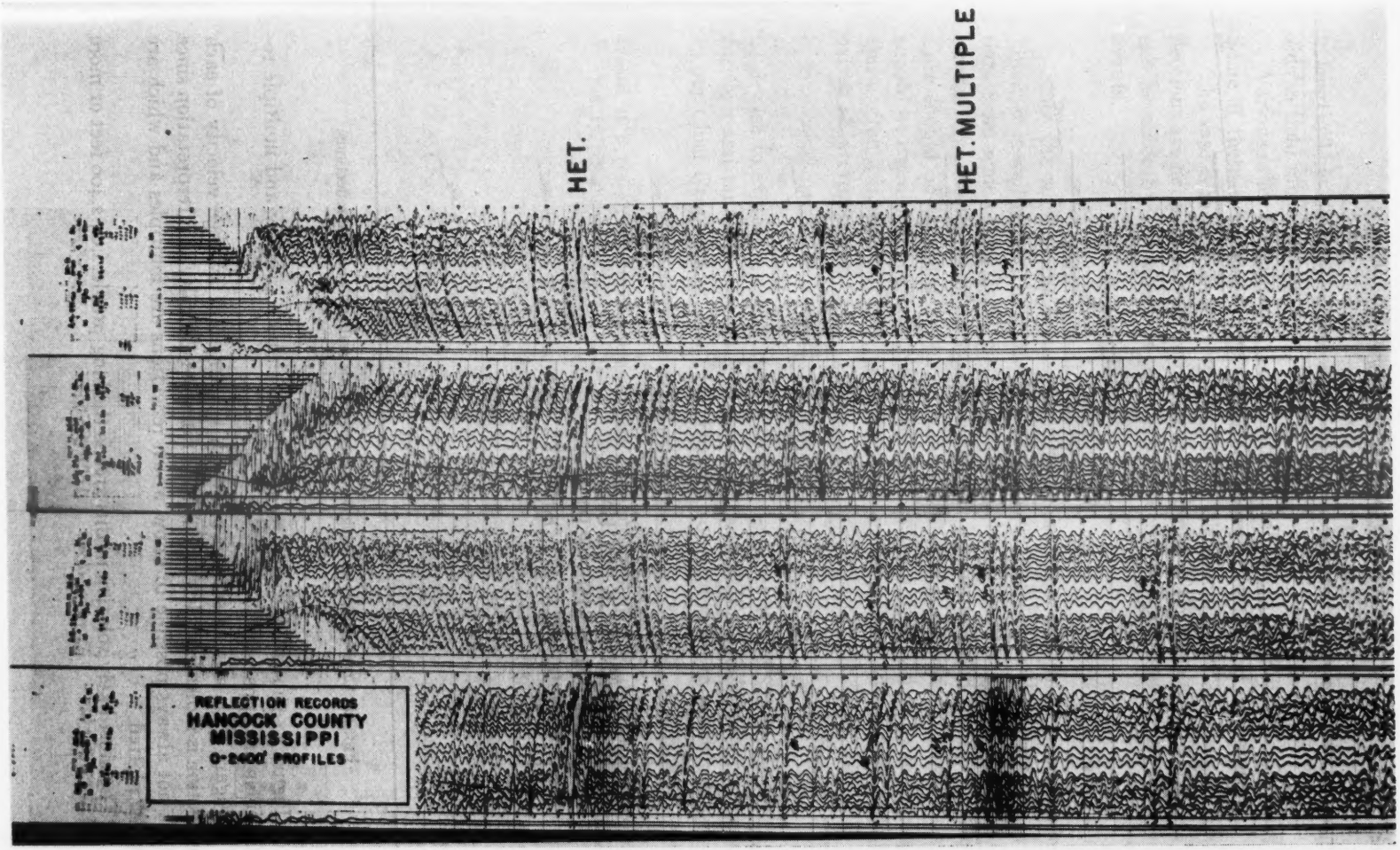

FIG. 11. Additional records showing multiple reflections.

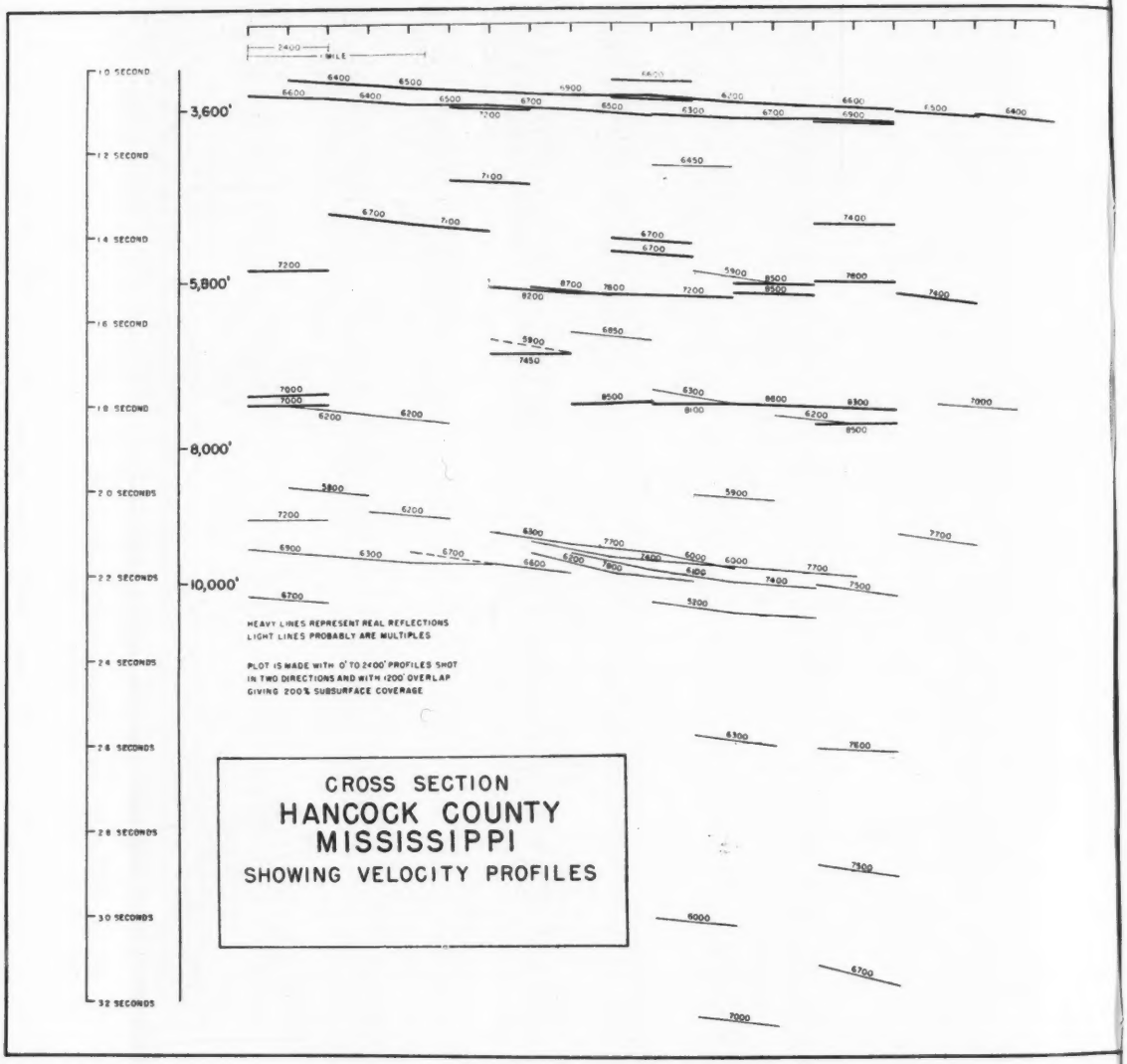

FIG. 12. Cross-section showing segments both for real and multiple reflections.

Figure 11 shows additional records on which both primary and multiple reflections are apparent.

Figure 12 is a cross-section on which the apparent average velocity of each reflection is indicated. This section illustrates the difficulty in interpretation since it is not always possible to know which reflections are multiples and which are to be plotted.

The most likely solution in this area is the long profile, i.e., 2,400 feet or more

in length. This allows X^2-T^2 velocity computations to be made on reflections and aids in their identification.

Various other attempts were made to try to eliminate the multiple reflections. Some of these techniques included pattern shots in the air and in the earth.

The case is more hopeful here than in the Plainview Basin, because deep reflections are actually present on the records. Maps of horizons below the "Het" can be made by the laborious process of velocity computation of all reflected events.

CONCLUSIONS

Since the work of the interpreter is becoming more exacting and more detailed, it is well to bear in mind that a map is no better than the quality of the data from which it is made. Attempts should be made to reduce the personal element by making use of all available velocity information and geological data. Care should be exercised in the selection of reflections for mapping and these should be examined for possible distortion by velocity variation or by multiples. Quite often it is apparent that many maps are made by using a little data and an excess of interpretation.

ACKNOWLEDGMENTS

I wish to express my appreciation to my associates at the Sun Oil Company for their assistance in assembling this material and to the Sun Oil Company and to our Chief Geophysicist, Dr. C. B. Bazzoni, for permission to publish it:

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DISPERSIVE PROPERTIES OF STRATIFIED ELASTIC AND LIQUID MEDIA: A RAY THEORY*

IVAN TOLSTOY† AND EUGENE USDIN†

ABSTRACT

The interference principle of wave guide propagation is applied to the derivation of the period equations for a number of problems involving both elastic and liquid strata. In the case of undamped steady state propagation in a solid or liquid stratum two arbitrarily chosen points at the same depth must be indistinguishable on an amplitude basis. This well known principle combined with the knowledge of the reflection coefficients enables us to derive in a few simple steps the period equations for a number of multilayer cases which heretofore had been avoided on account of algebraic difficulties. The period equations obtained by this method exhibit a singular simplicity and unity of form. As a consequence of this one may distinguish formally the M_1 and M_2 waves discovered by Sezawa and understand their physical significance.

INTRODUCTION

In 1948 C. L. Pekeris published a very thorough theoretical analysis (Pekeris, 1948) of normal mode propagation in stratified liquids. He showed that unattenuated propagation of sound would occur in a low-velocity liquid layer (sound velocity c_1) over a high-velocity liquid half space (sound velocity c_2) and that waves of this type were characterized by an infinite number of possible modes of propagation having nodal planes of pressure in the liquid. Each mode is dispersive and characterized by the existence of a minimum group velocity. Unattenuated propagation is of course possible only if the liquid surface layer has a lower velocity than the underlying liquid. In this case there exists for waves traveling within the layer a critical angle of incidence upon the boundary between the two liquids $\theta_c = \text{arc sin } c_1/c_2$. For angles of incidence $\theta > \theta_c$, there occurs total reflection and no energy is lost to the underlying medium. Pekeris showed that if a source be located within this surface layer, the disturbance recorded at a sufficient distance away is due entirely to the superposition of such totally reflected waves. In other words he proved that normal mode propagation in stratified liquids is a wave guide phenomenon. This interpretation enables one to obtain the dispersion or period equation for propagation of sound in stratified liquids without having to formulate the question as a boundary value problem for the wave equation. A little thought shows that for unattenuated propagation to be possible, the condition of total reflection by itself is not sufficient. It is also required that the totally reflected waves traveling within the layer do not annul each other by destructive interference but that they reinforce and form a self-sustaining traveling interference system. This is the criterion defining the angle of incidence (and therefore the apparent or phase velocity $c = c_1 \text{ cosec } \theta$) for which a given frequency of a particular mode will travel undestroyed in the layer. The

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corresponding group velocity U is given by the formula $U=d(kc)/dk$ where k is the wave number.

This method has been applied successfully to the somewhat more complex problem of a liquid layer overlying a semi-infinite elastic solid (Press and Ewing, 1948; Tolstoy, in press). In this case it was noted that the wave guide type of propagation explained only part of the picture. Thus unattenuated propagation is possible even when the speed of sound c_1 in the liquid exceeds the speed of shear waves β in the solid (Biot, 1952). This type of propagation is an interface or Stoneley wave and is dispersive as long as the ratio of thickness of the stratum to wave length is finite. In this case there are no higher modes, i.e. no modes of propagation with pressure nodes in the liquid. But if $c_1<\beta$ there exist higher modes which are due entirely to the wave-guide type of propagation. Furthermore, in this case that part of the fundamental mode propagation which corresponds to $c>c_1$ is also a wave-guide phenomenon. The branch of the fundamental mode which corresponds to $c<c_1$ is known as the Stoneley wave branch (Biot, 1952; Tolstoy, in press). The dispersion equation derived from the interference principle is still valid providing we replace $\cot\theta$ by $i\sqrt{1-(c^2/c_1^2)}$.

Therefore, in the case of a fluid layer overlying a semi-infinite elastic solid, the dispersion equation may be derived from the interference principle and the mechanism of propagation assumed by this principle completely explains all modes of propagation for which $c>c_1$. The dispersion equation one obtains in this case is compact and easy to use. Furthermore, it is applicable to the Stoneley wave branch if the above transformation be made. This transformation consists of passing from the domain of real to complex angles of incidence.

The present paper will describe the application of the interference principle to the case of stratified elastic media. We will start with a few simple plate problems (perfect elastic wave guides) and follow up with several problems of seismological interest. Among other things we believe we have settled the question of the so-called M_1 and M_2 branches of the Rayleigh wave dispersion curves.

We shall always assume unattenuated propagation in a direction parallel to the planes bounding the strata. This will be the x direction, the y coordinate being normal to the planes of the strata. We will assume that particle motion is limited to the xy plane.

CASES INCLUDING ELASTIC SOLIDS ONLY

Elastic Plate in Vacuum or Free Plate

If this plate had zero rigidity, the interference principle could be stated as follows: In order that unattenuated horizontal propagation of energy be possible all downward traveling components of a multiply reflected plane P wave must be in phase with the succeeding and preceding wave fronts (Press and Ewing, 1948; Tolstoy, in press). An equivalent statement can be made by considering a ray $ABCD$ (Fig. 1) reflected once from each boundary and by saying that the points A and D must be equivalent under steady state conditions. Given

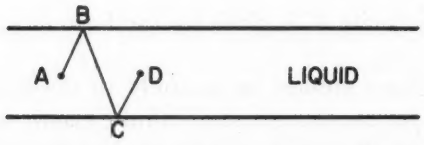

FIG. 1. Reflection of a ray $ABCD$ from each boundary of an elastic plate with zero rigidity.

an angle of incidence θ, this is possible for a discrete set of frequencies which correspond to the different unattenuated modes which will be associated with the phase velocity $c = c_1 \operatorname{cosec} \theta$, c_1 being the speed of sound in the plate. If the plate be an elastic solid the equivalence of the points A and D must be preserved, but the situation is somewhat complicated by the fact that both compressional (P) and shear (S) waves coexist in the solid. These waves travel with different velocities (α, β respectively) a wave of one type giving rise to reflected waves of both

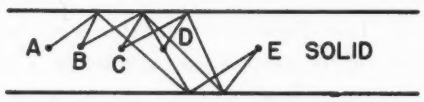

FIG. 2. Paths of contributions from points A, B, C, and D to E under steady state conditions in an elastic solid plate.

types. This difficulty was first resolved by Fay and Fortier (1951) in a paper on transmission of elastic waves by plates. Their reasoning is as follows:

Considering a point E (Fig. 2) we imagine a steady state condition corresponding to P waves incident at an angle θ, and S waves at an angle $\gamma = \text{arc sin } (\beta/\alpha \sin \theta)$. Then the contributions from points $ABCD$ will arrive simultaneously at E, the paths being traversed as:

A to E: PPP
B to E: SPP, PPS, PSP
C to E: SPS, SSP, PSS
D to E: SSS.

If we look at one displacement component, say the vertical component v, then we see that:

1) The sum of the v_P components of all waves arriving as P at E must be indistinguishable in the steady state from the v_P component at A.
2) The sum of all the v_S components due to waves arriving as S at E must be likewise indistinguishable from the v_S component of the S arrival at D (which itself may be considered as a superposition of four simultaneous arrivals corresponding to the above enumerated types of path).
3) Furthermore, in order that these two conditions be realizable it is necessary that the ratio v_P/v_S have a special value $\mathcal{R}$ which depends both upon the angle of incidence θ and the wave length $2\pi/k$. $\mathcal{R}$ can be obtained by

the solution of the system of simultaneous equations provided by conditions 1) and 2). The elimination of $\mathfrak{R}$ gives the period equation.[1]

In order to formulate these conditions we must know the values of the reflection coefficients for the vertical components of the various waves involved.

It will suffice to say that both in this and the following cases these coefficients are obtained by the usual means. Incident and derived waves are formulated in terms of Lamb's auxiliary functions ϕ and ψ, which are related to the horizontal and vertical displacement components by the equations:

$$u = \frac{\partial \phi}{\partial x} + \frac{\partial \psi}{\partial y}$$
$$v = \frac{\partial \phi}{\partial y} - \frac{\partial \psi}{\partial x}. \tag{1}$$

Incident and derived P waves are expressed in terms of ϕ functions, incident and derived S waves in terms of ψ functions. The boundary conditions yield the reflection coefficients in terms of the amplitudes of the corresponding ϕ and ψ functions (Jeffreys, 1926). These coefficients are immediately transformable into ratios of vertical component amplitudes by means of equation (1). We shall call the ratios of the vertical component amplitudes of derived waves to the vertical component of the incident wave "reflection coefficients for vertical components." We shall give these coefficients only, both in this and in all the cases that follow. By means of equation (1) the reader may easily transform these vertical component coefficients to either horizontal component coefficients or back to coefficients for the corresponding ϕ and ψ functions.

We shall omit all the steps leading to these coefficients, since the nature of these steps is well known indeed and the algebra is lengthy and quite devoid of interest both for the reader and the authors.

In the case of a free boundary an incident P wave (vertical component v_P) gives upon reflection a reflected P (vertical component v_P') and a reflected S (vertical component v_S''). An incident S (v_S) gives a reflected S (v_S') and a reflected P (v_P''). These four different kinds of reflections we call respectively PP, PS, SS, and SP type reflections. If θ be the angle of incidence of a P wave then the angle of reflection γ of the derived S wave shall be, by Snell's law:

$$\gamma = \arcsin\left(\frac{\beta}{\alpha}\sin\theta\right),$$

and vice versa, if γ be the angle of incidence of an S wave, the angle of reflection of the derived P wave shall be θ.

The vertical component reflection coefficients for the four types of reflection at a free surface are:

[1] The direct application of this principle gives the period equation in a general form. In order to calculate roots for any given range of phase velocities we merely convert this into a real equation.

$$
\begin{aligned}
PP \qquad & \frac{v_P'}{v_P} = A = \frac{(1 - \cot^2\gamma)^2 - 4\cot\theta\cot\gamma}{(1 - \cot^2\gamma)^2 + 4\cot\theta\cot\gamma} \\
PS \qquad & \frac{v_S''}{v_P} = B = \frac{-4(1 - \cot^2\gamma)}{(1 - \cot^2\gamma)^2 + 4\cot\theta\cot\gamma} \\
SS \qquad & \frac{v_S'}{v_S} = -A \\
SP \qquad & \frac{v_P''}{v_S} = C = \frac{-4\cot\theta\cot\gamma(1 - \cot^2\gamma)}{(1 - \cot^2\gamma)^2 + 4\cot\theta\cot\gamma}.
\end{aligned} \tag{2}
$$

Note that

$$A^2 + BC = 1. \tag{3}$$[2]

We can now formulate conditions 1), 2), and 3).
Condition 3) says:

$$\frac{v_P}{v_S} = \mathcal{R}. \tag{4}$$

Let us write

$$
\begin{aligned}
r &= k\cot\theta = k\sqrt{\frac{c^2}{\alpha^2} - 1} \\
s &= k\cot\gamma = k\sqrt{\frac{c^2}{\beta^2} - 1}.
\end{aligned} \tag{5}
$$

Looking at Figure 2 we see that there are four rays arriving at E as P waves. Of these two start out as P and two as S. By condition 3) the initial ratio of amplitudes has to be $v_P/v_S = \mathcal{R}$. The contribution of the PPP arrival at E may then be represented as $\mathcal{R}A^2e^{2irh}$, and the contribution of the PSP as $\mathcal{R}BCe^{irh}e^{ish}$. For the SPP and SSP contributions we have CAe^{2irh} and $-ACe^{irh}e^{ish}$ respectively. This gives us the following formulation for condition 1):

$$\mathcal{R}\{A^2e^{2irh} + BCe^{i(r+s)h}\} - ACe^{i(r+s)h} + ACe^{2irh} = \mathcal{R}. \tag{6a}$$

Similarly, by consideration of the rays arriving at E as S waves we obtain the following formulation for condition 2):

$$A^2e^{2ish} + BCe^{i(r+s)h} + \mathcal{R}\{ABe^{i(r+s)h} - ABe^{2ish}\} = 1. \tag{6b}$$

Eliminating $\mathcal{R}$ and using (3) we get

$$e^{i(r+s)h}[-BC + \cos(r+s)h - A^2\cos(r-s)h] = 0.$$

[2] This relation can also be obtained directly from Knott's energy relations.

Hence,

$$BC = \cos(r+s)h - A^2\cos(r-s)h \tag{7}$$

is the period equation. It may also be written in the form:

$$\frac{1-A}{1+A} = -\left[\frac{\tan r\frac{h}{2}}{\tan s\frac{h}{2}}\right]^{\pm 1}. \tag{8}$$

This is immediately reducible to Lamb's equations (Lamb, 1917) if we make

$$r = ir' = ik\sqrt{1-\frac{c^2}{\alpha^2}}$$

$$s = is' = ik\sqrt{1-\frac{c^2}{\beta^2}}$$

so that equation (8) becomes

$$\left[\frac{\tanh r'\frac{h}{2}}{\tanh s'\frac{h}{2}}\right]^{\pm 1} = \frac{4k^2r's'}{(k^2+s'^2)^2}. \tag{9}$$

If we take $+1$ for the exponent on the left hand side we have the so-called anti-symmetric modes of propagation, whereas if we take -1 for this exponent we have the symmetric modes of propagation.

a) The Symmetric Modes (M_1)

Symmetric propagation was so named by Lamb because the components of displacement in the plate are symmetric with respect to the median plane of the plate. For reasons that will become apparent we shall use the symbol M_1 for the symmetric modes. We shall distinguish an M_{11} or fundamental branch and the M_{12}, M_{13}, $\cdots$ branches. Figure 3 shows the M_{11} and M_{12} branches for the case where Poisson's assumption holds (Poisson's ratio $\nu=0.25$). C_R being the speed of Rayleigh waves on the surface of a semi-infinite elastic solid ($\nu=0.25$), the M_{11} branch has phase velocities $C_R \leqq c \leqq 2\sqrt{\frac{2}{3}}\beta$. That portion of it which corresponds to $c \geqq \beta$ is explainable in terms of real reflected body waves whereas the portion $c<\beta$ is not. For $kh\to 0$, $c\to U\to 2\sqrt{\frac{2}{3}}\beta$. This corresponds to a low frequency arrival traveling with a velocity of $\sim 0.9\alpha$. It is similar in nature to the "rod wave" in an elastic bar which corresponds to tensions and compressions of long wave length which travel with the velocity $\sqrt{Y/\rho}$, Y being Young's modulus

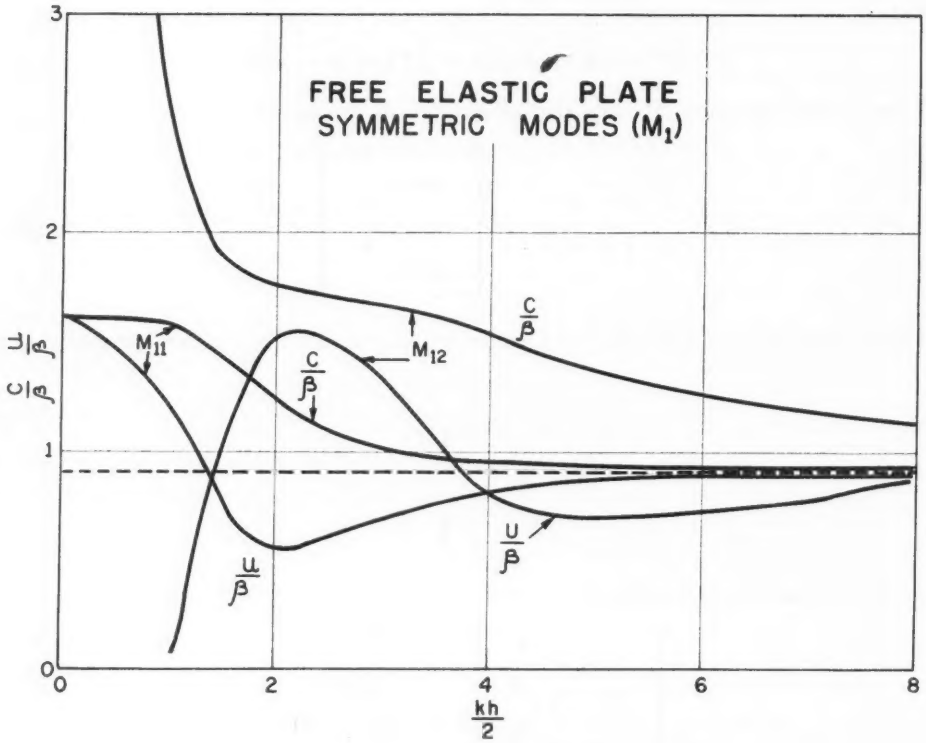

FIG. 3. Dispersion curves for symmetric modes in free elastic plate.

and ρ the density. The velocity is somewhat less than that of P waves in an infinite elastic medium because of the absence of transverse stress components and the resultant lowering of restitutive forces. For $kh \to \infty$, $c \to U \to C_R$. Here the motion for high frequencies degenerates into two Rayleigh waves in phase opposition traveling along each face of the plate. The group velocity has a minimum $kh \sim 4$, $U \sim 0.56\beta$. The higher modes such as M_{12} all have phase velocities $c > \beta$. For the M_{12} branch, when $kh \to 0$, $c \to \infty$, $U \to 0$ and for $kh \to \infty$, $c \to U \to \beta$. These higher modes also constitute analogs of the perfect acoustic wave guide. For intermediate frequencies, there exists a maximum group velocity at $kh \sim 4.2$, $U \sim 0.9\alpha$ and a minimum at $kh \sim 10$, $U \sim 0.7\beta$. The maximum group velocity of 0.9α corresponds to the "refracted P" of more complicated cases.[3]

b) *The Antisymmetric Modes* (M_2)

The components of displacement in the plate are antisymmetric with respect

[3] For increasing mode number (M_{1n}, $n \to \infty$) both this maximum and the corresponding phase velocity tend to α. Thus a discretely spaced set of high frequences will propagate with velocities approximating that of P waves. We believe this to be a very general phenomenon (for example, see Figures 4, 6, 8, 10.).

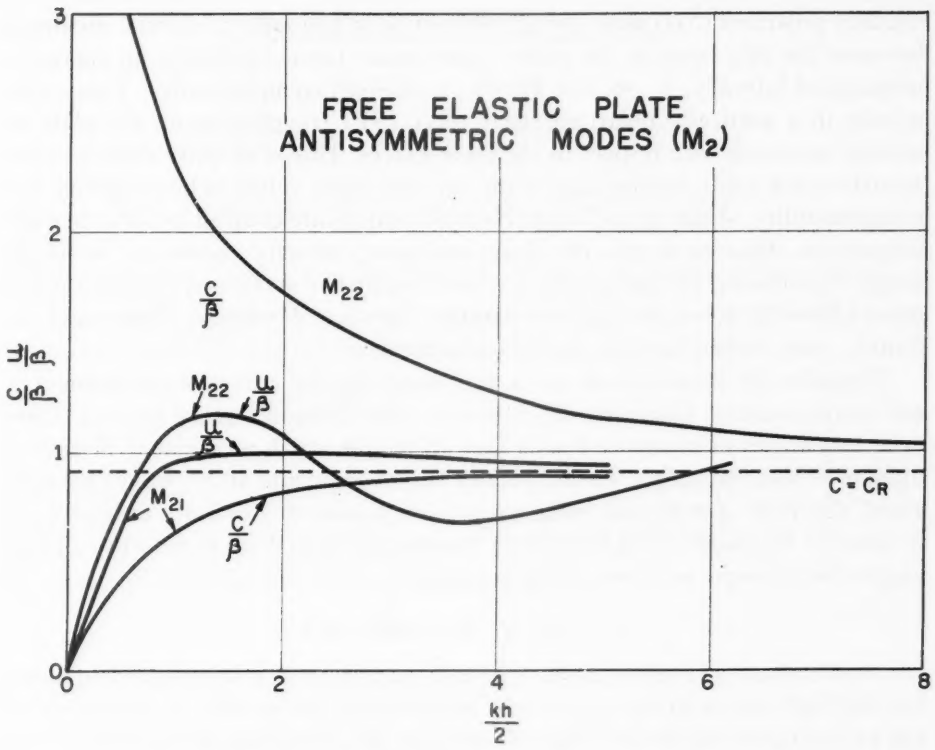

FIG. 4. Dispersion curves for antisymmetric modes in free elastic plate.

to the median plane of the plate. We shall use the symbol M_2 for these modes. There exist two types of antisymmetric propagation, in other words, two classes of branches M_{21}, and M_{22}, M_{23}, $\cdots$ (Fig. 4).

The M_{21} branch corresponds to $C_R \geqq c \geqq 0$, C_R being the speed of Rayleigh waves. If $kh \to 0$, $c \to U \to 0$. If $kh \to \infty$, $c \to U \to C_R$ (asymptotically). For high frequencies M_{21} propagation degenerates into two uncoupled Rayleigh waves in phase with respect to each other, one for each boundary. For intermediate frequencies, this branch has a broad group velocity maximum $kh \sim 3.6$, $U \sim \beta$.

Since for this branch all the functions on the left hand side of the period equation are hyperbolic it has, properly speaking, no higher modes. In other words it is not explainable in terms of real totally reflected body waves traveling within the plate. It corresponds to a flexural, purely shearing motion of the plate and owes its existence to the non-zero finite rigidity of the latter. It is of interest that the maximum group velocity is practically equal to the speed of shear waves.

The second branch M_{22} (or more exactly system of branches M_{22}, M_{23}, $\cdots$) of the antisymmetric type of propagation corresponds to $c > \beta$. This branch is explainable on the basis of totally reflected body waves; it is an elastic analog of the acoustic wave guide. For $kh \to 0$, $c \to \infty$ corresponding to a plane P or a hori-

zontally polarized (SH) wave being reflected back and forth at normal incidence between the two faces of the plate. Since under these conditions no energy is propagated laterally, $U \to 0$. For $kh \to \infty$, $c \to U \to \beta$ (asymptotically). This corresponds to a vertically polarized shear wave (SV) traveling along the plate at grazing incidence with respect to the plate's faces. This is all quite similar to the acoustic wave guide, but because of the non-zero finite values of both rigidity and compressibility, shearing and compressional motions are coupled for intermediate frequencies. Because of this the phase and group velocity curves are no longer simple hyperbolas. The group velocity has actually two stationary values: a maximum ($kh \sim 2.8$, $U \sim 1.2\beta$) and a minimum ($kh \sim 7.4$, $U \sim 0.7\beta$). There exist infinitely many modes for this type of propagation.

Equation (8) shows that if $A = 0$, the phase velocity curves of the symmetric and antisymmetric branches will intersect. For Poisson's ratio $\nu = 0.25$, there exist two angles of incidence θ such that $A = 0$, for which an incident P wave is upon reflection from a free surface totally transformed into an SV wave (Jeffreys, 1926), the angle of reflection being $\gamma = \arcsin(\beta/\alpha \sin\theta)$. Similarly a shear wave incident at this angle γ will be entirely transformed into P upon reflection. These angles are of course solutions of the equation

$$(1 - \cot^2\gamma)^2 = 4 \cot\theta \cot\gamma$$

which, if expressed in terms of phase velocity and squared, is the velocity equation for Rayleigh waves on the surface of a semi-infinite elastic solid. Examination of the period equations reveals that the M_{22} and M_{12} branches intersect for $c = 2\beta$, $c = \sqrt{2 + (2/\sqrt{3})}\beta$, which are two possible roots of this equation when $\nu = 0.25$. The "intersection" corresponding to the ordinarily used root of the Rayleigh wave equation $c = \sqrt{2 - (2/\sqrt{3})}\beta$ is actually a point of tangency and is approached asymptotically by the M_{11} and M_{12} branches for $kh \to \infty$. In order to convert the equation $A = 0$ into a polynomial equation one gets rid of the radicals by squaring. This squaring introduces extraneous roots since all the zeros of A and $1/A$ will appear as solutions of this equation. Actually the root $c = \sqrt{2 - (2/\sqrt{3})}\beta$ is a zero of $1/A$, not of A. If $\nu > 0.263$ it is a well known fact that the equation $A = 0$ may have no proper roots. In that case the intersections of the M_{22} and M_{12} branches may no longer occur.

It is of interest to remark that for $c < \alpha$, $r = k\sqrt{(c^2/\alpha^2) - 1}$ becomes imaginary. This corresponds to the fact that P waves traveling within the plate cannot have phase velocities less than α. Therefore, the body waves corresponding to the range $\beta \leqq c < \alpha$ must be shear waves. These shear waves are exceeding their "critical angle" of incidence at a free surface, $\gamma_c = \arcsin(\beta/\alpha)$ and are therefore being reflected as shear waves alone, with no change in amplitude and a change in phase of 2ζ, where

$$\zeta = \arctan\left[\frac{4\cot\gamma\sqrt{1 - \dfrac{\beta^2}{\alpha^2}\operatorname{cosec}^2\gamma}}{(1 - 2\cot^2\gamma)^2}\right].$$

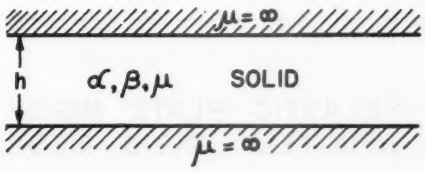

FIG. 5. Elastic layer inside an infinitely rigid medium of infinite extent.

An Elastic Layer Inside An Infinitely Rigid Medium of Infinite Extent (Fig. 5)

The reflection coefficients at the interface between an elastic medium and an infinitely rigid body are, for the vertical components:

$$\left.\begin{aligned} \frac{v_P'}{v_P} &= D = \frac{1 - \cot\theta\cot\gamma}{1 + \cot\theta\cot\gamma} & \frac{v_S'}{v_S} &= -D \\ \frac{v_S''}{v_P} &= E = \frac{-2}{1 + \cot\theta\cot\gamma} & \frac{v_P''}{v_S} &= F = \frac{-2\cot\theta\cot\gamma}{1 + \cot\theta\cot\gamma}. \end{aligned}\right\} \tag{10}$$

Between these coefficients, there exists the relation

$$D^2 + EF = 1. \tag{11}$$

Application of the interference principle to this case gives

$$\begin{aligned} \mathcal{R}[D^2e^{2irh} + EFe^{i(r+s)h}] - DFe^{i(r+s)h} + DFe^{2irh} &= \mathcal{R} \\ D^2e^{2ish} + EFe^{i(r+s)h} + \mathcal{R}[DEe^{i(r+s)h} - DEe^{2ish}] &= 1. \end{aligned} \tag{12}$$

By elimination of $\mathcal{R}$ and use of (11) we get

$$EF = \cos(r + s)h - D^2\cos(r - s)h \tag{13}$$

or

$$\left[\frac{\tan r\frac{h}{2}}{\tan s\frac{h}{2}}\right]^{\pm 1} = -\frac{1 - D}{1 + D}$$

which is formally identical with equation (8) for a free plate providing we replace A by D. In other words, we merely have to use the correct value for the PP reflection coefficient.

Here also there are two branches. If we take $+1$ as the exponent of the left hand side we have the antisymmetric mode of propagation or M_2 branch which corresponds to $c > \beta$ (Fig. 6). If $kh \to 0$, $c \to \infty$, $U \to 0$ and for $kh \to \infty$, $c \to U \to \beta$. The group velocity curve is monotonic throughout. Similarly for the symmetric mode $kh \to 0$, $c \to \infty$, $U \to 0$, and for $kh \to \infty$, $c \to U \to \beta$. The group velocity curve of the symmetric or M_1 mode has a maximum $kh \sim 3.2$, $U \sim 1.3\beta$ and a minimum $kh \sim 7.6$,

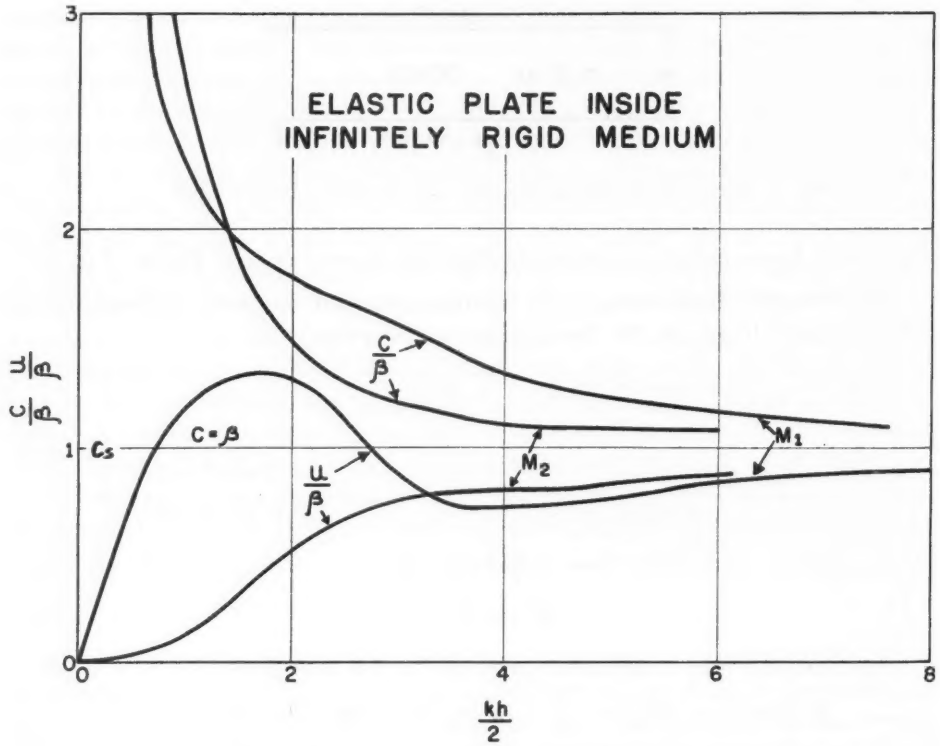

FIG. 6. Dispersion curves for elastic plate inside infinitely rigid medium.

$U \sim 0.7\beta$ for $\nu = 0.25$. These curves are quite reminiscent of the well known perfect acoustic wave guide curves (Tolstoy, in press). As in the case of the free plate we are dealing with a perfect elastic wave guide. However the picture here is simpler since boundary waves are prohibited due to the enforced immobility of the two boundaries.

Elastic Stratum Over an Infinitely Rigid Solid (Fig. 7)

The study of this case will give us the so-called theory of "Rayleigh waves" in the case of an elastic stratum of thickness h over an infinitely rigid half-space. We already have all the reflection coefficients for this case: at the free surface they are A, B, $-A$, C, as given by Equation (2) and at the interface between the two

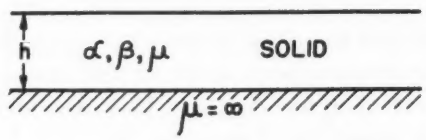

FIG. 7. Elastic stratum over an infinitely rigid solid.

media, they are D, E, $-D$, F as given by Equation (10). We can write down the interference conditions immediately in the form:

$$\begin{aligned} &\mathcal{R}[ADe^{2irh} + ECe^{i(r+s)h}] - CDe^{i(r+s)h} + AFe^{2irh} = \mathcal{R} \\ &ADe^{2ish} + BFe^{i(r+s)h} + \mathcal{R}[DBe^{i(r+s)ih} - AEe^{2ish}] = 1. \end{aligned} \tag{14}$$

Eliminating $\mathcal{R}$ and utilizing relations (11) and (3) and noting that $BF=CE$, we get the period equation in a very simple form:

$$BF = \cos(r+s)h - AD\cos(r-s)h \tag{15}$$

which may be rewritten in terms of the tangents of the half angles:

$$\tan r\frac{h}{2} = \frac{-2(1+AD)\tan s\frac{h}{2} \pm \sqrt{4(1+AD)^2\tan^2 s\frac{h}{2} - B^2F^2\left(1+\tan^2 s\frac{h}{2}\right)^2 + (1-AD)^2\left(1-\tan^2 s\frac{h}{2}\right)^2}}{BF\left(1+\tan^2 s\frac{h}{2}\right) + (1-AD)\left(1-\tan^2 s\frac{h}{2}\right)}. \tag{16}$$

Calculations were performed in this case by Sezawa and Kanai (1935a, 1935b).

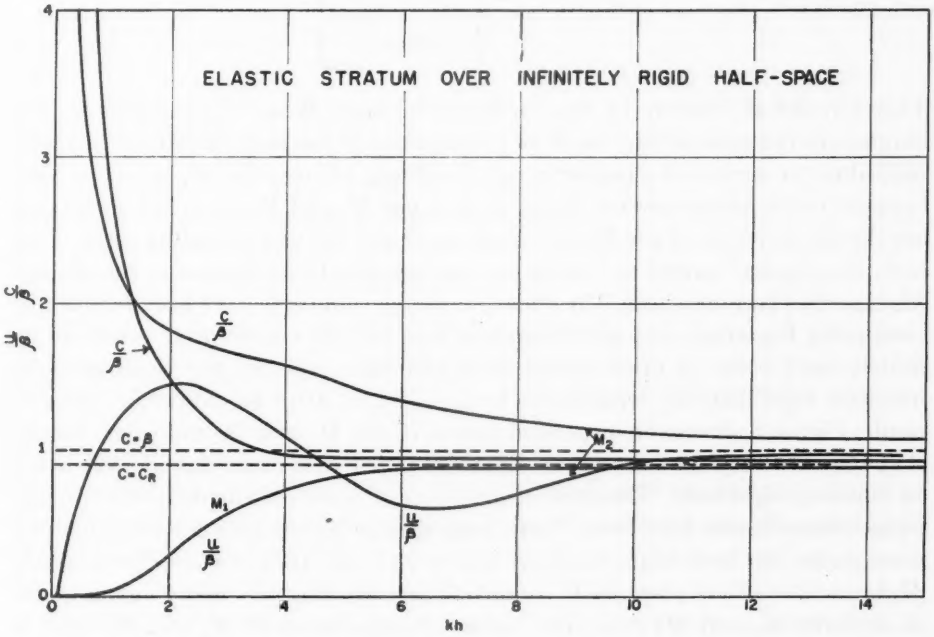

FIG. 8. Dispersion curves for elastic layer over infinitely rigid substratum.

They showed that there existed two branches which they called respectively M_1 and M_2. The M_1 branch corresponded to Rayleigh waves with a normal type retrograde elliptical particle motion whereas the M_2 branch corresponded to non-retrograde motion. We have verified numerically that these two branches exist: one of these (M_1) corresponding to the $-$ sign before the radical in (16), and the other (M_2) to the $+$ sign. Figure 8 shows these two branches for $\nu = 0.25$. Thus the mathematical formulation for the two branches becomes clear. But we may go further and gain some insight into the physical nature of these two branches by the following reasoning: Let us suppose that the underlying medium be replaced by a vacuum; then Equation (16) should reduce to Equation (9) for the free plate. If we replace in Equation (16) D by A, E by B and F by C, Equation (16) reduces in the case of the $-$ in front of the radical to

$$-\frac{1-A}{1+A} = \left[\frac{\tan r\dfrac{h}{2}}{\tan s\dfrac{h}{2}}\right]^{-1}$$

and in the case of the $+$ sign to

$$-\frac{1-A}{1+A} = \left[\frac{\tan r\dfrac{h}{2}}{\tan s\dfrac{h}{2}}\right].$$

Therefore the M_1 branch (i.e. the "ordinary Rayleigh Wave") in this case is what happens to the symmetrical mode of propagation of the free plate if the latter be welded to the surface of a perfectly rigid medium, whereas the M_2 branch is what happens to the antisymmetric mode, so that our M_1 and M_2 branches in this case are the counterparts of the M_1 and M_2 branches of the two preceding cases. Thus both the physical nature as well as the mathematical formulation of the M_1 and M_2 branches becomes clear. The above reasoning could also have been pursued by comparing Equation (16) with Equation (13) for the elastic plate inside an infinitely rigid body; in other words we would have replaced the vacuum by an infinitely rigid body by replacing B by E, C by F, A by D, obtaining the same result. Figure 8 shows the dispersion curves of the M_1 and M_2 branches. We see that they are very similar to those obtained in the case of an elastic layer inside an infinitely rigid body. The same general type of comments made in the two previous cases will also hold here. This elastic surface layer forms a perfect acoustic wave guide. For both branches if $kh \to 0$, $c \to \infty$, $U \to 0$. If $kh \to \infty$, $c \to U \to \beta$ for the M_2 branch, $c \to U \to C_R$ for the M_1 branch. There are infinitely many higher modes of both the M_1 and M_2 type. The phase velocity curves of M_1 and M_2 cross at $c/\beta = 2$. The group velocity curve of the M_1 branch is monotonic, whereas the group velocity curves of the M_2 type have both a maximum and a minimum.

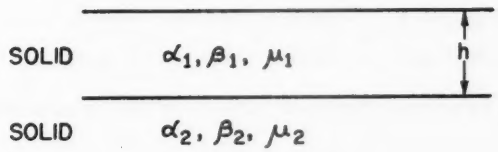

FIG. 9. Elastic surface layer over a semi-infinite elastic solid.

Elastic Surface Layer Over a Semi-infinite Elastic Solid (Fig. 9)

The derivation of the period equation follows the same steps as in the preceding cases. The most suitable notation for the reflection coefficients at the interface between two elastic media is that used by Muskat and Meres (1940).

Let $\alpha_1, \beta_1, \alpha_2, \beta_2$ be the body wave velocities of the two media, which we shall call media (1) and (2) respectively. Let μ_1, μ_2 be their rigidities. Using a notation analogous to that of Muskat and Meres we define a, b, d, e, f as:

$$\left.\begin{aligned} a &= \frac{\beta_2}{\beta_1} - 2\frac{\beta_2}{\beta_1}\sin^2\gamma_1 + 2\frac{\mu_2}{\mu_1}\frac{\beta_2}{\beta_1}\sin^2\gamma_1 \\ b &= \frac{\mu_2}{\mu_1}\cdot\frac{\beta_1}{\beta_2} - a \end{aligned}\right\} \tag{17}$$

$$\left.\begin{aligned} d &= \frac{\mu_2}{\mu_1}\left[\frac{\alpha_2}{\beta_2}\cos\theta_1\cos\gamma_2 + \frac{\alpha_1}{\beta_1}\cos\theta_2\cos\gamma_1\right] \\ \bar{d} &= \frac{\mu_2}{\mu_1}\left[\frac{\alpha^2}{\beta_2}\cos\theta_1\cos\gamma_2 - \frac{\alpha_1}{\beta_1}\cos\theta_2\cos\gamma_1\right] \\ e &= b^2\sin\theta_1\sin\theta_2 + \frac{\alpha_2}{\beta_1}\left(b + \frac{\beta_2}{\beta_1}\right)^2\cos\theta_1\cos\gamma_1 \\ \bar{e} &= b^2\sin\theta_1\sin\theta_2 - \frac{\alpha_2}{\beta_1}\left(b + \frac{\beta_2}{\beta_1}\right)^2\cos\theta_1\cos\gamma_1 \\ f &= \frac{\alpha_1}{\beta_2}\cos\theta_2\cos\gamma_2\left[a^2 + 4\frac{\beta_2}{\alpha_1}\frac{\beta_2}{\beta_1}\left(\frac{\mu_2}{\mu_1} - 1\right)^2\sin^2\gamma_1\cos\theta_1\cos\gamma_1\right] \\ \bar{f} &= \frac{\alpha_1}{\beta_2}\cos\theta_2\cos\gamma_2\left[a^2 - 4\frac{\beta_2}{\alpha_1}\frac{\beta_2}{\beta_1}\left(\frac{\mu_2}{\mu_1} - 1\right)^2\sin^2\gamma_1\cos\theta_1\cos\gamma_1\right] \end{aligned}\right\} \tag{18}$$

If we consider a plane P wave (v_{P1}) traveling in medium (1) and incident upon the boundary separating the two media with an angle of incidence θ_1, it will in general give rise to four waves: a reflected P (v_{P1}'), a reflected S (v_{S1}'') reflected at an angle γ_1, a transmitted P (v_{P2}') refracted at angle θ_2 and a transmitted S (v_{S2}'') refracted at an angle γ_2. Likewise an incident S wave (v_{S1}) incident at an angle γ_1, will give: a reflected S (v_{S1}'), a reflected P (v_{P1}'') reflected at an angle θ_1, a transmitted S (v_{S2}') refracted at an angle γ_2 and a transmitted P refracted at an angle θ_2. The angles of reflection and refraction are related by Snell's law:

$$\frac{\sin\theta_1}{\alpha_1} = \frac{\sin\theta_2}{\alpha_2} = \frac{\sin\gamma_1}{\beta_1} = \frac{\sin\gamma_2}{\beta_2}. \tag{19}$$

The corresponding vertical component reflection and transmission coefficients are then:

PP reflection $$\frac{v_{P1}'}{v_{P1}} = G = -\frac{\bar{d} - \bar{e} - \bar{f}}{d + e + f}$$

PS reflection $$\frac{v_{S1}''}{v_{P1}} = H = -\frac{2\sin\theta_1\sin\theta_2\left[b\left(b + \frac{\beta_2}{\beta_1}\right) + 2a\frac{\beta_1}{\alpha_2}\left(\frac{\mu_2}{\mu_1} - 1\right)\cos\theta_2\cos\gamma_2\right]}{d + e + f}$$

SS reflection $$\frac{v_{S1}'}{v_{S1}} = I = -\frac{\bar{d} + \bar{e} + \bar{f}}{d + e + f}$$

SP reflection $$\frac{v_{P1}''}{v_{S1}} = J = \cot\gamma_1\cot\theta_1 H$$

PP transmission $$\frac{v_{P2}'}{v_{P1}} = G' = \frac{2\frac{\alpha_1}{\beta_1}\cos\theta_2\left[\left(b + \frac{\beta_2}{\beta_1}\right)\frac{\beta_2}{\beta_1}\cos\gamma_1 + a\cos\gamma_2\right]}{d + e + f}$$

PS transmission $$\frac{v_{S2}''}{v_{P1}} = H' = \frac{2\frac{\beta_2}{\beta_1}\sin\theta_1\sin\theta_2\left[2\frac{\beta_2}{\alpha_2}\left(\frac{\mu_2}{\mu_1} - 1\right)\cos\theta_2\cos\gamma_1 - b\right]}{d + e + f}$$

SS transmission $$\frac{v_{S2}'}{v_{S1}} = I' = \frac{2\frac{\beta_2}{\beta_1}\frac{\alpha_2}{\beta_1}\cos\gamma_1\left[\frac{\alpha_1}{\alpha_2}a\cos\theta_2 + \left(b + \frac{\beta_2}{\beta_1}\right)\cos\theta_1\right]}{d + e + f}$$

SP transmission $$\frac{v_{P2}''}{v_{S1}} = J' = \frac{2\frac{\alpha_1}{\beta_1}\cot\gamma_1\sin\gamma_2\cos\theta_2\left[b - 2\frac{\beta_1}{\alpha_1}\left(\frac{\mu_2}{\mu_1} - 1\right)\cos\theta_1\cos\gamma_2\right]}{d + e + f}.$$

A little algebra enables one to prove the following very useful relations:

$$\begin{aligned} HJ - GI &= \frac{e + f - d}{e + f + d} \\ BJ &= CH. \end{aligned} \tag{20}$$

We may now derive the period equation for "Rayleigh waves" in the case of an elastic stratum overlying a semi-infinite elastic half space. Let h be the thickness of the surface layer. The interference condition gives:

$$\begin{aligned} \Re\left[AGe^{2ir_1h} + BJe^{i(r+s)h}\right] - AJe^{i(r+\epsilon)h} + CGe^{2ir_1h} &= \Re \\ -AIe^{2is_1h} + CHe^{i(r+s)h} + \Re\left[AHe^{i(r+s)h} + BIe^{2is_1h}\right] &= 1 \end{aligned} \tag{21}$$

eliminating $\Re$ we get

$$A\left[Ge^{2ir_1h} - Ie^{2is_1h}\right] + e^{2i(r+s)h}\left[GI - HJ\right] + 2e^{i(r+s)h}CH = 1. \tag{22}$$

Considering the case where the stratum has lower body wave velocities than the underlying medium, let us suppose that the critical angle is exceeded by the body waves in the stratum: $\sin\gamma_1 > \beta_1/\beta_2$. The latter assumption is necessary since

without it there could be no unattenuated horizontal propagation. It is then useful to alter slightly the notation of equations (17) and (18) by writing

$$\cos\theta_2 = im, \qquad m > 0$$
$$\cos\gamma_2 = in, \qquad n > 0$$
$$\frac{\mu_2}{\mu_1}\frac{\alpha_2}{\beta_2} n\cos\theta_1 = g$$
$$\frac{\mu_2}{\mu_1}\frac{\alpha_1}{\beta_1} m\cos\gamma_1 = h \tag{23}$$
$$b^2\sin\theta_2\sin\theta_1 - a^2mn\frac{\alpha_1}{\beta_2} = j$$
$$\cos\theta_1\cos\gamma_1\left[\frac{\alpha_2}{\beta_1}\left(b+\frac{\beta_2}{\beta_1}\right)^2 - 4\frac{\beta_2}{\beta_1}\left(\frac{\mu_2}{\mu_1}-1\right)^2 mn\sin^2\gamma_1\right] = k.$$

In this case, the reflection coefficients G, H, I, J become complex, and we have:

$$GI - HJ = -e^{-2i\epsilon} = -\frac{j+k-i(g+h)}{j+k+i(g+h)}, \qquad \epsilon = \arctan\frac{g+h}{j+k}$$
$$G = \frac{j-k-i(g-h)}{j+k+i(g+h)} = \Gamma e^{-i(\bar\epsilon+\epsilon)}, \qquad \bar\epsilon = \arctan\frac{g-h}{j-k}$$
$$I = -\frac{j-k+i(g-h)}{j+k+i(g+h)} = -\Gamma e^{-i(\epsilon-\bar\epsilon)}$$
$$H = \Lambda e^{-i\epsilon} \tag{24}$$
$$\Gamma = \sqrt{\frac{(j-k)^2+(g-h)^2}{(j+k)^2+(g+h)^2}}$$
$$\Lambda = \frac{-2\sin\theta_1\sin\theta_2\left[b\left(b+\dfrac{\beta_2}{\beta_1}\right) - 2amn\dfrac{\beta_1}{\alpha_2}\left(\dfrac{\mu_2}{\mu_1}-1\right)\right]}{\sqrt{(j+k)^2+(g+h)^2}}.$$

Γ is therefore the modulus of I and of G, Λ is the modulus of H. Hence the period equation reduces to:

$$C\Lambda = \cos\left[(r+s)h - \epsilon\right] - A\Gamma\cos\left[(r-s)h - \bar\epsilon\right] \tag{25}$$

where: A, C are the PP and SP free surface reflection coefficients, Γ is the modulus of the PP reflection coefficient at the interface between the two elastic media, Λ is the modulus of the PS reflection coefficient at this interface, $-(\bar\epsilon+\epsilon)$, $-\epsilon$ are the corresponding changes in phase suffered upon total reflection from the interface.

The simplicity of form of this equation is striking. It has several advantages:

Computations are somewhat shortened, and the coefficients A, C, Γ, Λ all have a direct physical interpretation in terms of the reflection of plane waves. Furthermore, it is an easy matter to convert this equation into terms of the tangents of the half angles and thereby to resolve once and for all the question of the nature of the so-called M_2 branch (Kanai, 1951). We may rewrite equation (25) in the form:

$$\tan r\frac{h}{2}=\frac{\left(1-\tan^2 s\frac{h}{2}\right)(\sin\epsilon-A\Gamma\sin\bar{\epsilon})-2\tan s\frac{h}{2}(\cos\epsilon+A\Gamma\cos\bar{\epsilon})}{2\tan s\frac{h}{2}(\sin\epsilon+A\Gamma\sin\bar{\epsilon})+\left(1+\tan^2 s\frac{h}{2}\right)\Lambda C-\left(\tan^2 s\frac{h}{2}-1\right)(\cos\epsilon-A\Gamma\cos\bar{\epsilon})}$$
$$\pm\frac{\sqrt{\left(1+\tan^2 s\frac{h}{2}\right)^2(1+A^2\Gamma^2-\Lambda^2C^2)+2A\Gamma\left[4\tan^2 s\frac{h}{2}\cos(\epsilon-\bar{\epsilon})-\left(1-\tan^2 s\frac{h}{2}\right)^2\cos(\epsilon-\bar{\epsilon})-4\tan s\frac{h}{2}\left(1-\tan^2 s\frac{h}{2}\right)\sin(\epsilon-\bar{\epsilon})\right]}}{2\tan s\frac{h}{2}(\sin\epsilon+A\Gamma\sin\bar{\epsilon})+\left(1+\tan^2 s\frac{h}{2}\right)\Lambda C-\left(\tan^2 s\frac{h}{2}-1\right)(\cos\epsilon-A\Gamma\cos\bar{\epsilon})}. \quad (25)$$

If we make the underlying medium infinitely rigid, ϵ and $\bar{\epsilon}$ go to zero, Γ becomes D and Λ becomes E. The above equation reduces to Equation (16), showing that in the case where the underlying medium has finite elastic constants the distinction between the M_1 and M_2 branches persists. Since the + sign before the radical in equation (25) corresponds to the + sign before the radical in equation (16), the M_2 branch in this case will correspond to the antisymmetrical

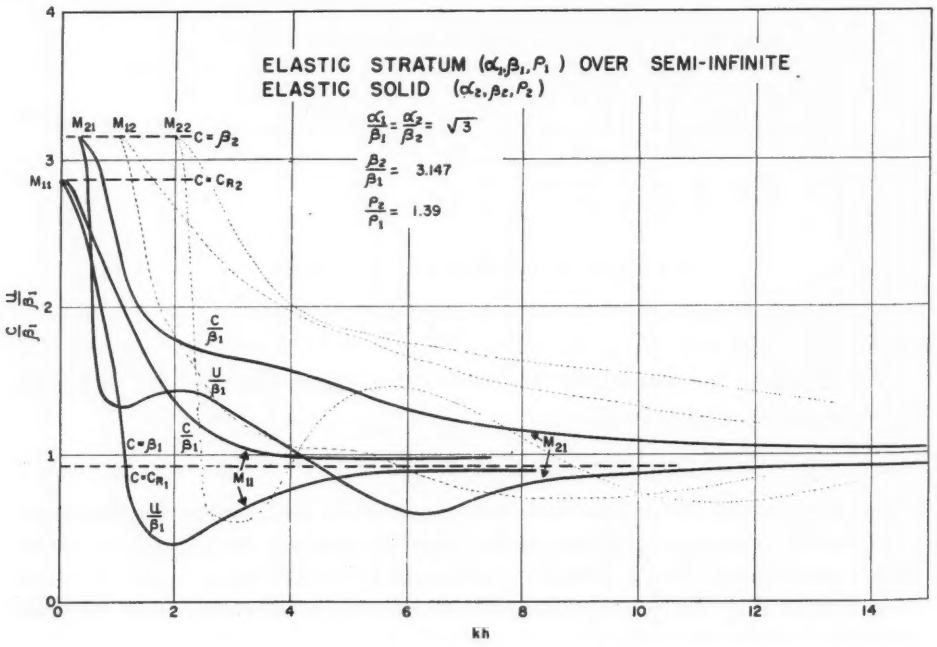

FIG. 10. Dispersion curves for elastic layer over semi-infinite elastic substratum.

mode of a free plate modified by welding this plate to the surface of a semi-infinite elastic solid. The M_1 branch is the symmetrical mode of this plate modified for the same reasons. Both the M_1 and M_2 types of propagation are characterized by infinitely many modes of propagation. Figure 10 shows the phase and group velocities for the first two modes of the M_1 and M_2 branches (M_{11}, M_{12} and M_{21}, M_{22}) for the case: $\rho_2/\rho_1 = 1.39$, $\mu_2/\mu_1 = 13.77$, $\nu_1 = \nu_2 = 0.25$. This case was chosen because the first mode of the M_1 branch had previously been calculated by Lee (1932) and Jardetzky and Press (1952), thus providing a check on our calculations. It is of interest to note that if we assume that $c < \beta_1$ and $kh \to \infty$, equation (25) gives

$$\frac{1}{A\Gamma} = 0.$$

We have already noted that $1/A = 0$ is the velocity equation of non-dispersive Rayleigh waves on the surface of a semi-infinite medium having the same elastic properties as the surface layer. In other words for high frequencies at least one branch of the dispersion curves tends asymptotically to the speed of Rayleigh waves in medium (1). The equation

$$\frac{1}{\Gamma} = 0$$

can be shown to be formally identical with the velocity equation for Stoneley waves (Stoneley, 1924) at the interface between the two media (1) and (2), both of these being semi-infinite in extent. Unfortunately, for the parameters chosen for Figure 10, the conditions for existence of a Stoneley wave are not satisfied (Scholte, 1947; Sezawa, 1939). We can be certain, however, that in the case where Scholte's and Sezawa's criteria for the existence of Stoneley waves are satisfied, there shall exist two asymptotic velocities for high frequencies: the Rayleigh wave velocity for the upper medium and the Stoneley wave velocity at the interface between the two media. We expect this Stoneley wave velocity to be approached asymptotically by a branch which does not appear in those cases for which the Stoneley wave existence conditions are not satisfied. This branch corresponds to the M_{21} branch of the free plate modified by the presence of an elastic substratum and is associated with phase velocities less than the velocity of Stoneley waves.

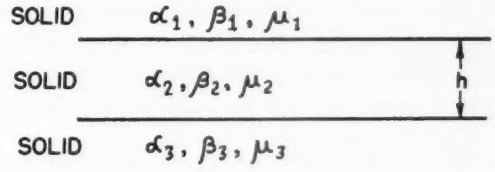

FIG. 11. Elastic stratum between two different semi-infinite media.

Elastic Stratum Between Two Different Semi-infinite Media (Fig. 11)

Let (1) and (3) be subscripts referring to the two semi-infinite media, and let the stratum be medium (2) of thickness h_2. Application of the interference principle gives immediately:

$$\Delta_1\Delta_3 = \cos\left[(r_2 + s_2)h_2 - \epsilon_3 - \epsilon_1\right] - \Gamma_1\Gamma_3 \cos\left[(r_2 - s_2)h_2 - \bar{\epsilon}_3 - \bar{\epsilon}_1\right] \quad (26)$$

where $\Delta_1 (\equiv \cot\theta_2 \cot\gamma_2 \Lambda_1)$ is the modulus of the *SP* reflection coefficient at the (1)-(2) interface. It should be noted that in order to secure exponentially decreasing amplitudes in media (1) and (3) away from the stratum, we have to define:

$$\cos\theta_3 = im_3 \ (m_3 > 0), \qquad \cos\gamma_3 = in_3 \ (n_3 > 0)$$
$$\cos\theta_1 = im_1 \ (m_1 < 0), \qquad \cos\gamma_1 = in_1 \ (n_1 < 0).$$

The asymptotic velocities for very high frequencies are here given by the equation:

$$\frac{1}{\Gamma_1\Gamma_3} = 0,$$

showing that we may expect two Stoneley waves traveling with different velocities, one for each boundary (providing that the elastic parameters allow these waves to exist).

Elastic Stratum Inside an Elastic Medium of Infinite Extent

This is just a special case of the preceding problem. When media (1) and (3) are identical, equation (25) becomes:

$$\Delta\Lambda = \cos\left[(r_2 + s_2)h_2 - 2\epsilon\right] - \Gamma^2 \cos\left[(r_2 - s_2)h_2 - 2\bar{\epsilon}\right]$$

or in another familiar form:

$$\frac{1 - \Gamma}{1 + \Gamma} = -\left[\frac{\tan\left(r\dfrac{h}{2} - \dfrac{\epsilon + \bar{\epsilon}}{2}\right)}{\tan\left(s\dfrac{h}{2} - \dfrac{\epsilon - \bar{\epsilon}}{2}\right)}\right]^{\pm 1}.$$

Here the two branches M_1 and M_2 correspond to truly symmetric and antisymmetric modes of propagation. This is of course due to the symmetry of the problem. The phase velocity curves were previously obtained by Sezawa from less simple equations (Sezawa, 1928). In this case for very high frequencies, one may have two Stoneley waves traveling with the same velocity along the two boundaries of the stratum: if the exponent on the right hand side of the above equation is $+1$, they are in phase; they are out of phase in the other case.

CASES INCLUDING BOTH ELASTIC SOLIDS AND LIQUIDS

We have derived several other period equations to illustrate the power of the

interference principle in obtaining period equations and the simplicity and unity of form of the equations obtained in this fashion. We must first obtain the vertical component reflection coefficients at the interface between an elastic medium and a liquid. Let medium (1) be a solid and medium (2) a liquid. Let α_1, β_1 be the velocities of P and S waves in medium (1) and let ρ_1 be its density. Let α_2 be the speed of sound in medium (2) and ρ_2 the density there.

If a plane P wave (v_{P1}) traveling in medium (1) be incident at the boundary between media (1) and (2) at the angle θ_1, it gives upon reflection and transmission: a reflected P (v_{P11}'), a reflected S (v_{S11}'') reflected at an angle γ_1, and a transmitted P (v_{P12}') refracted at an angle θ_2. Likewise an incident S (v_{S1}) incident at an angle γ_1 will give: a reflected S (v_{S11}'), a reflected P (v_{P11}'') reflected at an angle θ_1, and a transmitted P (v_{P12}'') refracted at an angle θ_2. A plane P wave (v_{P2}) traveling within medium (2) and incident upon the (2)-(1) interface with an angle θ_2 will give: a reflected P (v_{P22}'), a transmitted P (v_{P21}') refracted at an angle θ_1 and a transmitted S (v_{S21}'') refracted at an angle γ_1. The angles $\theta_1, \theta_2, \gamma_1$ are related by Snell's law.

If then we use the notation:

$$\begin{aligned} 4 \cos\theta_1 \cot\gamma_1 \cot\theta_2 &= p \\ \cot\theta_2(\cot^2\gamma_1 - 1)^2 &= q \\ \frac{\rho_2}{\rho_1} \cot\theta_1 \cdot \operatorname{cosec}^4\gamma_1 &= t. \end{aligned} \tag{27}$$

The vertical component reflection and transmission coefficients become:

$$\left.\begin{aligned} \frac{v_{P11}'}{v_{P1}} = K = -\frac{p-q+t}{p+q+t} \qquad & \frac{v_{S11}'}{v_{S1}} = P = \frac{p-q-t}{p+q+t} \\ \frac{v_{S11}''}{v_{P1}} = L = \frac{4\cot\theta_2(\cot^2\gamma_1 - 1)}{p+q+t} \qquad & \frac{v_{P11}''}{v_{S1}} = Q = \frac{p(\cot^2\gamma_1 - 1)}{p+q+t} \\ \frac{v_{P12}'}{v_{P1}} = M = \frac{2\cot\theta_2(\cot^2\gamma_1 - 1)\operatorname{cosec}^2\gamma_1}{p+q+t} \qquad & \frac{v_{P12}''}{v_{S1}} = R = \frac{p\operatorname{cosec}^2\gamma_1}{p+q+t} \\ \frac{v_{P22}'}{v_{P2}} = S = -\frac{p+q-t}{p+q+t} & \\ \frac{v_{S21}''}{v_{P2}} = U = \frac{4\cot\theta_1\operatorname{cosec}^2\gamma_1 \cdot \frac{\rho_2}{\rho_1}}{p+q+t} & \\ \frac{v_{P21}'}{v_{P2}} = T = \frac{2\cot\theta_1\operatorname{cosec}^2\gamma_1(\cot^2\gamma_1 - 1)\frac{\rho_2}{\rho_1}}{p+q+t}. & \end{aligned}\right\} \tag{28}$$

The following relations between the coefficients are immediately apparent:

$$\left.\begin{aligned} MU - LS &= L \\ RT - QS &= Q \\ PS - RU &= K \\ KS - MT &= P \\ PK - LQ &= S \\ QMU &= LRT \\ PMT + RUK - QMU - LRT &= \frac{-4t(p+q)}{(p+q+t)^2} \\ \frac{RU}{MT} &= \frac{p}{q}. \end{aligned}\right\} \tag{29}$$

Elastic Stratum Overlying a Semi-Infinite Liquid

If we assume that the elastic stratum (medium (1)) has lower body wave velocities than the underlying liquid (medium (2)), and that total reflection occurs, K, P, L, Q become complex, $p=ip'$, $q=iq'$. Writing:

$$\Omega = \sqrt{\frac{(q'-p')^2+t^2}{(q'+p')^2+t^2}} \qquad \Pi = \frac{4l_2(\cot^2\gamma_1 - 1)}{\sqrt{(q'+p')^2+t^2}}$$

$$\cot\theta_2 = il_2, \qquad l_2 > 0 \qquad \eta = \arctan\frac{-t}{p'+q'}$$

$$\Phi = \frac{4l_2\cot\theta_1\cot\gamma_1(\cot^2\gamma_1 - 1)}{\sqrt{(q'+p')^2+t^2}} \qquad \bar{\eta} = \arctan\frac{-t}{q'-p'}$$

we have:

$$\begin{aligned} S &= -e^{-2i\eta} \\ K &= \Omega e^{-i(\eta+\bar{\eta})} \\ P &= -\Omega e^{-i(\eta-\bar{\eta})} \\ L &= \Pi e^{-i\eta} \\ Q &= \Phi e^{-i\eta} = L\cot\theta_1\cot\gamma_1. \end{aligned}$$

And applying the interference principle in the familiar fashion, we obtain in a few simple steps the period equation:

$$C\Pi = \cos[(r+s)h - \eta] - A\Omega\cos[(r-s)h - \bar{\eta}] \tag{30}$$

where h is the thickness of the stratum, and r, s have their usual definitions. Ω and Π are the moduli of the PP and PS reflection coefficients. Equation (30)

is thus formally identical with the period equation (25) for the case of a solid elastic substratum providing we substitute the correct expressions for the reflection coefficients and phase changes. Note that here for $c<\beta_1$, if we make $kh\to\infty$, we get

$$\frac{1}{A\Omega} = 0,$$

where $1/\Omega=0$ is now the velocity equation for Stoneley waves at the interface between a semi-infinite elastic solid (medium (1)) and a semi-infinite liquid (medium (2)) (Biot, 1952; Tolstoy, in press).

Elastic Stratum Between Two Different Semi-Infinite Liquids

Let the liquid on one side of the plate be medium (1) (α_1, ρ_1), the liquid on the other be medium (3) (α_3, ρ_3) and the elastic plate be medium (2) (α_2, β_2, ρ_2). Then by a suitable reshuffling of subscripts, and application of the interference principle to the case of total reflection of body waves traveling within the plate we get

$$\Phi_1\Pi_3 = \cos\left[(r_2+s_2)h_2-\eta_1-\eta_3\right]-\Omega_1\Omega_3\cos\left[(r_2-s_2)h_2-\bar{\eta}_1-\bar{\eta}_3\right]. \quad (31)$$

The high frequency asymptotic velocities are given by the equation

$$\frac{1}{\Omega_1\Omega_3} = 0$$

so that we shall have two Stoneley waves, one for each face of the plate.

Elastic Plate in an Infinite Liquid

This is the case where the liquids (1) and (3) become identical so that we have:

$$\Phi\Pi = \cos\left[(r_2+s_2)h_2-2\eta\right]-\Omega^2\cos\left[(r_2-s_2)h_2-2\bar{\eta}\right], \quad (32)$$

which may be rewritten as:

$$\frac{1-\Omega}{1+\Omega} = -\left[\frac{\tan\left(r\frac{h}{2}-\frac{\eta+\bar{\eta}}{2}\right)}{\tan\left(s\frac{h}{2}-\frac{\eta-\bar{\eta}}{2}\right)}\right]^{\pm 1}.$$

This form emphasizes the similarity of the equation with that of the free plate. It reduces very easily to the equations obtained by Osborne and Hart, (1945). Here for high frequencies we have the asymptotic velocities given by

$$\frac{1}{\Omega} = 0$$

and the motion degenerates into either two Stoneley waves in phase opposition, (when the exponent is -1), or in phase (when the exponent is $+1$).

Semi-Infinite Liquid over an Elastic Stratum over a Semi-Infinite Elastic Solid

$$\Phi\Lambda = \cos\left[(r_2 + s_2)h_2 - \epsilon - \eta\right] - \Omega\Gamma\cos\left[(r_2 - s_2)h_2 - \bar{\epsilon} - \bar{\eta}\right]. \quad (33)$$

This is the equation explaining the so-called "Air-coupled Rayleigh waves," (Jardetzky and Press, 1952). If the liquid be replaced by a vacuum $\eta\to\infty$, $\Phi\to C$, and the equation reduces to Equation (25). It should be noted that there is a Stoneley wave at the interface between the solid stratum and the fluid, the velocity equation of which is, of course

$$\frac{1}{\Omega} = 0$$

As pointed out earlier if Scholte's and Sezawa's conditions are satisfied there will also exist a Stoneley wave at the interface between the two elastic media, the velocity equation of which is

$$\frac{1}{\Gamma} = 0.$$

Elastic Stratum Over a Liquid Layer Over a Semi-Infinite Elastic Solid (*Figure 12*)

The period equation for this case is of interest to seismologists since it could correspond to actual conditions in continental areas. In these areas there may

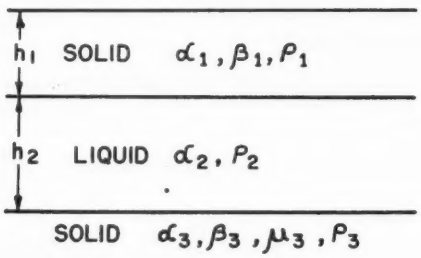

FIG. 12. Elastic stratum over a liquid layer overlying a semi-infinite elastic solid.

exist an incompetent layer incapable of transmitting shear between the overlying granitic layer and the underlying ultrabasics (Press and Ewing, 1952).

The method applied in a three-layered problem of this type is analogous to the one indicated in the "3-liquid-layers case" by Officer (1951). We consider as arriving at a given point in the solid stratum:

1) a set of arrivals similar to those studied in the preceding cases:

PPP	*PSP*	*SSP*	*SPP*
SSS	*SPS*	*PPS*	*PSS*

for which the reflection at the solid (1)-liquid (2) interface may be either partial or total.

2) a set of infinitely many reflections within the liquid to be added to each of the preceding groups of possible paths after multiplication by the corresponding transmission coefficients. Calling V the reflection coefficient at the (2)-(3) interface, this set is represented by the series:

$$\sum = Ve^{2ir_2h_2} + SV^2e^{4ir_2h_2} + S^2V^3e^{6ir_2h_2} + \cdots$$
$$= \frac{Ve^{2ir_2h_2}}{1 - VSe^{2ir_2h_2}} \tag{34}$$

The interference principle then gives

$$\Re[Ae^{2ir_1h_1}(K + MT\sum) + Ce^{i(r_1+s_1)h_1}(L + MU\sum)]$$
$$+ Ce^{i(r_1+s_1)h_1}(P + RU\sum) + Ae^{2ir_1h_1}(Q + RT\sum) = \Re$$
$$- Ae^{2is_1h_1}(P + RU\sum) + Be^{i(r_1+s_1)h_1}(Q + RT\sum)$$
$$+ \Re[Be^{i(r_1+s_1)h_1}(K + MT\sum) - Ae^{2is_1h_1}(L + MU\sum)] = 1$$

For unattenuated propagation of body waves guided by the surface strata to be possible, it is necessary that conditions of total reflection be met at at least one of the interfaces. Thus we can conceive of total reflection at the (2)-(3) interface, or at the (1)-(2) interface, or at both (P waves traveling within the liquid layer). However we know that the period equation derived on the basis of any one of these three assumptions can be transformed to fit all of these cases. It is sufficient therefore for us to derive the period equation in real form for the first case (total reflection at the (2)-(3) interface). Under this condition

$$V = -e^{-2i\omega}$$

where

$$\omega = \arctan \frac{\frac{\rho_2}{\rho_3}\frac{c^4}{\beta_3^4}\left(1 - \frac{c^2}{\alpha_3^2}\right)^{1/2}\tan\theta_2}{\left(2 - \frac{c^2}{\beta_3^2}\right)^2 - 4\left(1 - \frac{c^2}{\alpha_3^2}\right)^{1/2}\left(1 - \frac{c^2}{\beta_3^2}\right)^{1/2}}.$$

$\pi - 2\omega$ is the change in phase suffered by a plane P wave traveling within the liquid (2) upon total reflection from the (2)-(3) solid interface. ω is the $\epsilon/2$ of the paper in press by Tolstoy. Elimination of $\Re$ and use of equations (29) and (30) gives the period equation for this case:

$$S\sin[(r_1 + s_1)h_1 - r_2h_2 + \omega] + \sin[(r_1 + s_1)h_1 + r_2h_2 - \omega]$$
$$+ AK\sin[(r_1 - s_1)h_1 - r_2h_2 + \omega]$$
$$+ AP\sin[(r_1 - s_1)h_1 + r_2h_2 - \omega] - 2LC\sin[r_2h_2 - \omega] = 0. \tag{35}$$

If total reflection were occurring from the (1)-(2) interface, r_2 would become imaginary, K, L, N, P would be complex, and equation (35) would have to be transformed to be solved.

Liquid Stratum Over an Elastic Stratum Over a Semi-Infinite Elastic Solid

Let the liquid be medium (1), the elastic stratum be medium (2), and the semi-infinite elastic solid be medium (3). Then keeping the same notation as for the preceding cases, the interference principle gives the period equation:

$$\begin{aligned} S \cos\left[(r_2 + s_2)h_2 - r_1h_1 - \epsilon\right] - \cos\left[(r_2 + s_2)h_2 + r_1h_1 - \epsilon\right] \\ + \Gamma K \cos\left[(r_2 - s_2)h_2 - r_1h_1 - \bar{\epsilon}\right] \\ - \Gamma P \cos\left[(r_2 - s_2)h_2 + r_1h_1 - \bar{\epsilon}\right] + 2\Lambda Q \cos r_1h_1 = 0. \end{aligned} \tag{36}$$

Finally, we may get the period equation for *the case where the liquid stratum in the above model is overlain by a semi-infinite fluid* (0). If we write

$$\chi = \operatorname{arc\,cot}\left[\frac{\rho_1}{\rho_0}\sqrt{\tan^2\theta_1 - \frac{\alpha_1^2}{\alpha_0^2}\sec^2\theta_1}\right]$$

for the change in phase upon total reflection within the liquid (1) at the boundary between the two liquids.[4] The period equation becomes:

$$\begin{aligned} S \cos\left[(r_2 + s_2)h_2 - r_1h_1 - \epsilon - \chi\right] - \cos\left[(r_2 + s_2)h_2 + r_1h_1 - \epsilon + \chi\right] \\ + \Gamma K \cos\left[(r_2 - s_2)h_2 - r_1h_1 - \bar{\epsilon} - \chi\right] \\ - \Gamma P \cos\left[(r_2 - s_2)h_2 + r_1h_1 - \bar{\epsilon} + \chi\right] \\ + 2\Lambda Q \cos\left[r_1h_1 + \chi\right] = 0. \end{aligned} \tag{37}$$

This would be the dispersion equation for Rayleigh waves crossing an ocean, the presence of sediments (taken as solid elastic media), water, and air being taken into account.

CONCLUSIONS

We believe that this paper has illustrated the advantages of the interference principle for the determination of period equations for stratified elastic and liquid media. First, if used in conjunction with such simplifying relations as equations (29), (20), (11) and (3), it enables one to obtain the period equations in a few simple steps. The period equations (26), (35), (36) and (37) would have been very tedious to obtain by the usual procedure of determinant expansion. The reader will find that after a little practice and with the proper use of the relations between reflection coefficients he can derive these equations in a matter

[4] This is the half change in phase for the vertical component of displacement and is therefore the complement of the half change in phase for the velocity potential usually used in these problems (as formulated by Rayleigh).

of minutes. In this paper we have limited ourselves to a few very simple cases, since there appears to be almost no limit to the complexity of the problems for which the period equation may be obtained by a proper use of the method.

Secondly, it is obvious that this principle yields the period equation in an extremely simple form. As a consequence of this, we have been able to confirm formally Sezawa's remarkable numerical discovery of the existence of the two "Rayleigh wave" branches M_1 and M_2 in the case of an elastic layer overlying a semi-infinite elastic solid, and to understand their physical significance. Thirdly, the form of the equation obtained by this method is physical. In other words each coefficient has a direct physical significance: it is either a reflection coefficient or the modulus thereof. Thus, the computation of any set of dispersion curves automatically entails the computation of reflection and transmission coefficients both real and complex (total reflection).

All the necessary reflection and transmission coefficients have been given explicitly in the course of our investigation. With the current availability of machine methods of computation it is to be hoped that very complete tabulations of all reflection and transmission coefficients will be performed, thus making the computation of large numbers of dispersion curves a comparatively trifling problem.

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ON THE THEORY OF HEAD WAVES*

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ABSTRACT

When a combined longitudinal and transverse disturbance, diverging from a localized source, strikes a plane boundary between two solid elastic media, several systems of head waves and second-order boundary waves are generated, each associated with grazing incidence of one or the other of the reflected or refracted waves. Associated with grazing incidence of $P_1\underline{P}_2$, the refracted P-wave, is the head wave system comprising $P_1P_2P_1$ (the "refracted wave" of seismic prospectors), and $P_1P_2S_1$ (a transverse head wave) in the upper medium, and $P_1P_2\underline{S}_2$ (a transverse head wave) in the lower medium. There is no boundary wave in the lower medium. These three waves, with the second-order term of $P_1\underline{p}_2$ (the first-order term is zero on the boundary) satisfy conditions of continuity of stress and displacement at the boundary. Moreover, the energy of the three head waves is derived completely from the second-order component of $P_1\underline{P}_2$, which possesses a component of energy flow normal to the boundary. The amplitudes of $P_1P_2P_1$, $P_1P_2S_1$ and $P_1P_2\underline{S}_2$ are calculated for certain cases.

REFLECTION AND REFRACTION AT A PLANE INTERFACE: FORMAL SOLUTION

In a previous paper by the author (Heelan, 1953), the mathematical form of the field radiated by a cylindrical cavity of finite length under certain prescribed conditions of stress was presented. The purpose of that study was to obtain an approximate expression for the disturbance generated by the detonation of a charge in a cylindrical shot hole. It was assumed there that the impulsive stresses acting at the source could be represented by a certain outward pressure $p(t)$, a vertical shearing stress $q(t)$, and a horizontal shearing stress $s(t)$. As far as the following work is concerned, however, the source of the radiating disturbance can be taken to be any localized disturbance in the upper medium radiating P, SV, and SH waves of which the horizontal and vertical particle displacements (predominant terms only) can be respectively expressed in the following forms: for P,

$$\begin{bmatrix} u_P \\ w_P \end{bmatrix} = \begin{bmatrix} \dfrac{F_1(\phi)}{R} \dfrac{d}{dt}\{p(t - R/V)\} \end{bmatrix} \begin{bmatrix} \sin\phi \\ -\cos\phi \end{bmatrix}; \tag{1}$$

for SV,

$$\begin{bmatrix} u_{SV} \\ w_{SV} \end{bmatrix} = \begin{bmatrix} \dfrac{F_2(\phi)}{R} \dfrac{d}{dt}\{p(t - R/v)\} \end{bmatrix} \begin{bmatrix} \cos\phi \\ \sin\phi \end{bmatrix}; \tag{2}$$

and for SH,

$$v_{SH} = \frac{K(\phi)}{R} \frac{d}{dt}\{s(t - R/v)\}, \tag{3}$$

where (see Figure 1)

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$$R^2 = r^2 + (d - Z)^2, \qquad \tan \phi = r/(d - Z).$$

For the particular case of a small cylindrical source of the type considered in the previous paper, $p(t)$, as we have shown, represents the outward lateral pressure at the source, and $s(t)$ the horizontal shearing stress. The vertical shearing stress, $q(t)$ of the previous paper, is assumed to be zero. In this case,

$$F_1(\phi) = \Delta(1 - [2v^2 \cos^2 \phi]/V^2)/4\pi\mu V$$
$$F_2(\phi) = \Delta \sin 2\phi/4\pi\mu v$$
$$K(\phi) = \Delta \sin \phi/4\pi\mu v,$$

where Δ = volume of the cylindrical source,
μ = rigidity of the medium,
V, v = velocities of P and S waves respectively.

We now proceed to examine how the incident radiation is modified by the presence of a plane discontinuity in the medium.

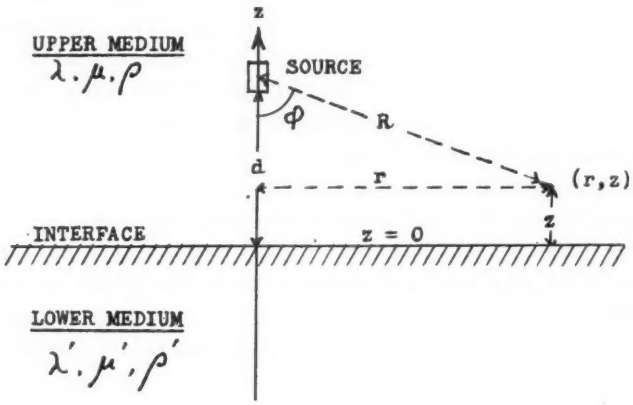

FIG. 1. Geometry of system.

It is supposed that the center of the disturbance is located at the point $z = d$, $r = 0$ in a medium of elastic constants λ and μ and of density ρ filling the half-space $z > 0$. The half-space $z < 0$ is occupied by a medium of elastic constants λ' and μ' and of density ρ' (see Figure 1).

The primary incident radiation generated by the source has the form of the three auxiliary wave functions,

$$\Phi_0 = \int_0^\infty e^{ikVt} dk \int_C f_0 H_0^{(1)}(\sigma r) e^{\alpha(z-d)} d\sigma$$
$$\Theta_0 = \int_0^\infty e^{ikVt} dk \int_C g_0 H_0^{(1)}(\sigma r) e^{\beta(z-d)} d\sigma$$
$$\chi_0 = \int_0^\infty e^{ikVt} dk \int_C n_0 H_0^{(1)}(\sigma r) e^{\beta(z-d)} d\sigma,$$

where $\alpha=(\sigma^2-k^2)^{1/2}$, $\beta=(\sigma^2-h^2)^{1/2}$, $kV=hv$, and C is a loop $(\infty i, -k, -h, \infty i)$ where arg. $\sigma=$ arg. $\alpha=$ arg. $\beta=\pi/2$ initially, and $2\pi \geqq$ arg. $\sigma \geqq 0$ on the path. Φ_0 represents the incident longitudinal wave, Θ_0 the incident SV wave, and χ_0 the incident SH wave. These integrals are assumed to give waves of the type represented by equations (1) at large distances from the source. For the case of the small cylindrical source treated in the previous paper, the functionals f_0, g_0 and n_0 assume the following forms at large distances from the source:

$$f_0 = p_1(k)\Delta\sigma(2\sigma^2/h^2 + 1 - 2v^2/V^2)/8\pi\mu(\sigma^2 - k^2)^{1/2},$$

$$g_0 = p_1(k)\Delta\sigma/4\pi\mu h^2,$$

$$n_0 = s_1(k)\Delta\sigma/4\pi\mu(\sigma^2 - h^2)^{1/2},$$

where $p_1(k)$ and $s_1(k)$ satisfy the relationships

$$p(t) = \mathrm{Rl}\int_0^\infty p_1(k)\exp(ikVt)dk$$

and

$$s(t) = \mathrm{Rl}\int_0^\infty s_1(k)\exp(ikVt)dk,$$

Rl designating the real portion of the integrals.

The expressions for the waves themselves are given in equations (1) to (3).

Let Φ, Θ, χ be the auxiliary wave functions[1] of the reflected longitudinal, SV and SH disturbances respectively, and Φ', Θ', χ' the corresponding functions for the transmitted disturbance. These must satisfy the following equations.

$$\frac{\partial^2\Phi}{\partial t^2} - V^2\nabla^2\Phi = 0; \qquad \frac{\partial^2\Phi'}{\partial t^2} - V'^2\nabla^2\Phi' = 0$$

$$\frac{\partial^2\Theta}{\partial t^2} - v^2\nabla^2\Theta = 0; \qquad \frac{\partial^2\Theta'}{\partial t^2} - v'^2\nabla^2\Theta' = 0$$

$$\frac{\partial^2\chi}{\partial t^2} - v^2\nabla^2\chi = 0; \qquad \frac{\partial^2\chi'}{\partial t^2} - v'^2\nabla^2\chi' = 0$$

where $V=(\lambda+2\mu)^{1/2}/\rho^{1/2}$, $v=\mu^{1/2}/\rho^{1/2}$, $V'=(\lambda'+2\mu')^{1/2}/\rho'^{1/2}$, $v'=\mu'^{1/2}/\rho'^{1/2}$.

It is now assumed that $\Phi, \Theta, \chi, \Phi', \Theta'$, and χ' can be expressed as integrals in the following way:

[1] The particle displacements (u, v, w) in the directions of r, θ, z respectively increasing, are given by the formulas:

$$u = \frac{\partial\Phi}{\partial r} - \frac{\partial^2\Theta}{\partial r\partial z}, \qquad w = \frac{\partial\Phi}{\partial z} + \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial\Theta}{\partial r}\right), \qquad v = \frac{\partial\chi}{\partial r}.$$

$$\begin{aligned}
\Phi &= \int_0^\infty e^{ikVt}dk \int_C f_1 H_0^{(1)}(\sigma r)e^{-\alpha z}d\sigma \\
\Theta &= \int_0^\infty e^{ikVt}dk \int_C g_1 H_0^{(1)}(\sigma r)e^{-\beta z}d\sigma \\
\chi &= \int_0^\infty e^{ikVt}dk \int_C n_1 H_0^{(1)}(\sigma r)e^{-\beta z}d\sigma \\
\Phi' &= \int_0^\infty e^{ikVt}dk \int_C f' H_0^{(1)}(\sigma r)e^{-\alpha' z}d\sigma \\
\Theta' &= \int_0^\infty e^{ikVt}dk \int_C g' H_0^{(1)}(\sigma r)e^{-\beta' z}d\sigma \\
\chi' &= \int_0^\infty e^{ikVt}dk \int_C n' H_0^{(1)}(\sigma r)e^{-\beta' z}d\sigma
\end{aligned} \tag{4}$$

where $kV = hv = k'V' = h'v'$, and C is now an enlarged contour including the additional branch points $-k'$ and $-h'$, and any other singularity of the integrands that provides a physically interpretable result.[2]

Expressing the continuity of particle displacement and stress across the plane $z = 0$, six linear equations are obtained for the six functional unknowns. Solving these equations, it is found that

$$\left.\begin{aligned}
f_1 &= [f_0 D_1 \exp(-\alpha d) + g_0 D_2 \exp(-\beta d)]/D \\
g_1 &= [f_0 D_3 \exp(-\alpha d) + g_0 D_4 \exp(-\beta d)]/D \\
n_1 &= n_0(\mu\beta - \mu'\beta')(\mu\beta + \mu'\beta')^{-1} \exp(-\beta d) \\
f' &= [f_0 D_1' \exp(-\alpha d) + g_0 D_2' \exp(-\beta d)]/D \\
g' &= [f_0 D_3' \exp(-\alpha d) + g_0 D_4' \exp(-\beta d)]/D \\
n' &= 2n_0\mu\beta(\mu\beta + \mu'\beta')^{-1} \exp(-\beta d)
\end{aligned}\right\} \tag{5}$$

where the coefficients D, D_1, etc. are given by the following sets of equations, in which $\xi = 2\sigma^2 - h^2$ and $\xi' = 2\sigma^2 - h'^2$:

$$D = \alpha' P + Q \tag{6}$$

where

$$\begin{aligned}
P &= 4\alpha\beta\beta'\sigma^2(\mu' - \mu)^2 - \beta(\mu\xi - 2\mu'\sigma^2)^2 - \mu\mu' h^2 h'^2\beta \\
Q &= -\alpha\beta(\mu'\xi' - 2\mu\sigma^2)^2 - \mu\mu' h^2 h'^2\alpha\beta' + \sigma^2(\mu'\xi' - \mu\xi)^2 \\
D_1 &= \alpha' P_1 + Q_1
\end{aligned} \tag{7}$$

[2] The wave system associated with the singularity must be of divergent type and finite at infinty, *cf.* Sommerfeld, A. (1912).

where

$$P_1 = 4\alpha\beta\beta'\sigma^2(\mu' - \mu)^2 + \beta'(\mu\xi - 2\mu'\sigma^2)^2 + \mu\mu' h^2 h'^2\beta$$

$$Q_1 = -\alpha\beta(\mu'\xi' - 2\mu\sigma^2)^2 - \mu\mu' h^2 h'^2\alpha\beta' - \sigma^2(\mu'\xi' - \mu\xi)^2$$

$$D_2 = \beta' P_2 + Q_2 \tag{8}$$

where

$$P_2 = 4\alpha'\beta\sigma^2(\mu' - \mu)(\mu\xi - 2\mu'\sigma^2)$$

$$Q_2 = 2\beta\sigma^2(\mu'\xi' - \mu\xi)(\mu'\xi' - 2\mu\sigma^2),$$

$$D_3 = \alpha' P_3 + Q_3 \tag{9}$$

where

$$P_3 = 4\alpha\beta'(\mu' - \mu)(\mu\xi - 2\mu'\sigma_2)$$

$$Q_3 = 2\alpha(\mu'\xi' - \mu\xi)(\mu'\xi - 2\mu\sigma^2)$$

$$D_4 = \beta' P_4 + Q_4 \tag{10}$$

where

$$P_4 = 4\alpha\alpha'\beta\sigma^2(\mu' - \mu)^2 + \alpha'(\mu\xi - 2\mu'\sigma^2)^2 + \mu\mu' h^2 h'^2\alpha$$

$$Q_4 = -\mu\mu' h^2 h'^2\alpha'\beta - \alpha\beta(\mu'\xi' - 2\mu\sigma^2)^2 - \sigma^2(\mu'\xi - \mu\xi)^2,$$

$$D_1' = 2\mu h^2\alpha\beta(\mu'\xi' - 2\mu\sigma^2) + 2\mu h^2\alpha\beta'(\mu\xi - 2\mu'\sigma^2) \tag{11}$$

$$D_2' = \beta' P_2' + Q_2' \tag{12}$$

where

$$P_2' = 4\mu h^2\alpha\beta\sigma^2(\mu' - \mu)$$

$$Q_2' = -2\mu h^2\beta\sigma^2(\mu'\xi' - \mu\xi)$$

$$D_3' = \alpha' P_3' + Q_3' \tag{13}$$

where

$$P_3' = 4\mu h^2\alpha\beta(\mu' - \mu)$$

$$Q_3' = -2\mu h^2\alpha(\mu'\xi' - \mu\xi)$$

and

$$D_4' = 2\mu h^2\alpha\beta(\mu'\xi' - 2\mu\sigma^2) + 2\mu h^2\alpha'\beta(\mu\xi - 2\mu'\sigma^2). \tag{14}$$

When the functionals (equations (5)) are substituted into their respective integrals, it is seen that the reflected and transmitted longitudinal disturbances are each composed of two parts, one involving f_0 and consequently the incident P wave, and the other g_0 and the incident SV wave. The reflected and transmitted SV disturbances are similarly composed. Only SH acts independently and is reflected and transmitted wholly without change of type.

Reflected Longitudinal Disturbance.—Changing over to actual particle displacements, the reflected longitudinal disturbance in the upper medium is found to be the sum of: 1. (u_1, w_1) which yields, as we shall see later, the principal reflected PP wave as its principal part, and 2. (u_2, w_2) which yields SP as its principal part, where

$$\left.\begin{aligned} u_1 &= -\int_C \frac{\sigma f_0 D_1}{D} H_1^{(1)}(\sigma r) e^{-\alpha(z+d)} d\sigma \\ w_1 &= -\int_C \frac{\alpha f_0 D_1}{D} H_0^{(1)}(\sigma r) e^{-\alpha(z+d)} d\sigma \end{aligned}\right\} \tag{15}$$

$$\left.\begin{aligned} u_2 &= -\int_C \frac{\sigma g_0 D_2}{D} H_1^{(1)}(\sigma r) e^{-\alpha z - \beta d} d\sigma \\ w_2 &= -\int_C \frac{\alpha g_0 D_2}{D} H_0^{(1)}(\sigma r) e^{-\alpha z - \beta d} d\sigma \end{aligned}\right\}. \tag{16}$$

Reflected SV Disturbance.—This is composed of: 1. (u_3, w_3) which yields PS, and 2. (u_4, w_4) which yields SS. Here

$$\left.\begin{aligned} u_3 &= -\int_C \frac{\sigma\beta f_0 D_3}{D} H_1^{(1)}(\sigma r) e^{-\beta z - \alpha d} d\sigma \\ w_3 &= -\int_C \frac{\sigma^2 f_0 D_3}{D} H_0^{(1)}(\sigma r) e^{-\beta z - \alpha d} d\sigma \end{aligned}\right\} \tag{17}$$

$$\left.\begin{aligned} u_4 &= -\int_C \frac{\sigma\beta g_0 D_4}{D} H_1^{(1)}(\sigma r) e^{-\beta(z+d)} d\sigma \\ w_4 &= -\int_C \frac{\sigma^2 g_0 D_4}{D} H_0^{(1)}(\sigma r) e^{-\beta(z+d)} d\sigma \end{aligned}\right\}. \tag{18}$$

Reflected SH Disturbance.—This has only one term v_1 which corresponds to SS (horizontally polarized). Here,

$$v_1 = -\int_C \frac{\mu\beta - \mu'\beta'}{\mu\beta + \mu'\beta'} \sigma q_0 H_1^{(1)}(\sigma r) e^{-\beta(z+d)}. \tag{19}$$

Transmitted Longitudinal Disturbance.—This is composed of two parts, 1. (u_1', w_1') which gives $P\underline{P}$,[3] and 2. (u_2', w_2') which gives $S\underline{P}$. Here,

[3] The underbar denotes a path in the lower medium.

$$\left.\begin{aligned} u_1' &= -\int_C \frac{\sigma f_0 D_1'}{D} H_1^{(1)}(\sigma r) e^{\alpha' z - \alpha d} d\sigma \\ w_1' &= \int_C \frac{\alpha' f_0 D_1'}{D} H_0^{(1)}(\sigma r) e^{\alpha' z - \alpha d} d\sigma \end{aligned}\right\} \tag{20}$$

$$\left.\begin{aligned} u_2' &= -\int_C \frac{\sigma g_0 D_2'}{D} H_1^{(1)}(\sigma r) e^{\alpha' z - \beta d} d\sigma \\ w_2' &= \int_C \frac{\alpha' g_0 D_2'}{D} H_0^{(1)}(\sigma r) e^{\alpha' z - \beta d} d\sigma \end{aligned}\right\}. \tag{21}$$

Transmitted SV Disturbance.—This likewise, is composed of two parts: 1. (u_3', w_3') which gives $\underline{PS}$, and 2. (u_4', w_4') which gives $\underline{SS}$. Here,

$$\left.\begin{aligned} u_3' &= -\int_C \frac{\sigma \beta' f_0 D_3'}{D} H_1^{(1)}(\sigma r) e^{\beta' z - \alpha d} d\sigma \\ w_3' &= -\int_C \frac{\sigma^2 f_0 D_3'}{D} H_0^{(1)}(\sigma r) e^{\beta' z - \alpha d} d\sigma \end{aligned}\right\} \tag{22}$$

$$\left.\begin{aligned} u_4' &= \int_C \frac{\sigma \beta' g_0 D_4'}{D} H_1^{(1)}(\sigma r) e^{\beta' z - \beta d} d\sigma \\ w_4' &= -\int_C \frac{\sigma^2 g_0 D_4'}{D} H_0^{(1)}(\sigma r) e^{\beta' z - \beta d} d\sigma \end{aligned}\right\}. \tag{23}$$

Transmitted SH Disturbance.—This has only one term v', which corresponds to $\underline{SS}$ (horizontally polarized). Here,

$$v' = -\int_C \frac{2\mu\sigma\beta n_0}{\mu\beta + \mu'\beta'} H_1^{(1)}(\sigma r) e^{\beta' z - \beta d} d\sigma. \tag{24}$$

In each of the preceding formulas, the operation $\int_0^\infty \cdots e^{ikVt}\, dk$ (real part) has been omitted merely for convenience in writing the expressions. It is understood to apply to each of the integrals numbered (15) to (24).

The preceding formulas comprise the complete formal solution of the problem of reflection and transmission of a given disturbance at a plane interface separating two solid media. In the next paper, it will be shown that each of these integrals, when evaluated, yields a number of terms, some of the first order, delineating the major portion of the effect under ordinary conditions, and others of the second-order, among which are included many forms of head waves. These head waves will be the subject of the following two sections.

NATURE OF WAVE SYSTEMS GENERATED BY REFLECTION AND REFRACTION AT A PLANE BOUNDARY

The expressions (15) to (24) which describe the particle displacements in the two media, constitute the formal solution of the problem of reflection and refraction of a disturbance at a plane interface between two media. As they stand, however, they do not yield much information about the nature of the separate wave systems generated at the boundary. In the neighborhood of the source, a quantitative description of the disturbance would require a laborious numerical integration. For most practical purposes it is sufficient to consider what happens at distances from the source sufficiently large to justify the use of asymptotic expansions in inverse powers of the distance from the source.

The general method to be used in obtaining asymptotic expansions involves a deformation of the path of integration C, so that the predominant terms can be procured by successive applications of Watson's Lemma (Copson, 1935) to segments of the path. This method has been employed successfully in similar problems by Nakano, Sezawa, Kanai, Nishimura, Sakai, Scholte and others (see, for example Nakano, 1925).

Consider the first of the integrals numbered (15), namely,

$$u_1 = -\int_C \frac{\sigma D_1 f_0}{D} H_1^{(1)}(\sigma r) e^{-(z+d)\alpha} d\sigma.$$

When $|\sigma r| \gg 0$ at all points on the path C, it is possible to replace the Hankel function by its asymptotic expansion,

$$\sqrt{\frac{2}{\pi\sigma r}} e^{i\sigma r - 3\pi i/4}.$$

Putting $z+d = R_1 \cos\epsilon$, $r = R_1 \sin\epsilon$ (see Figure 2) and $m_1(\sigma) = \alpha \cos\epsilon - i\sigma \sin\epsilon$, the integral then reduces to

$$-\sqrt{\frac{2}{\pi r}} \int_C \frac{\sigma^{1/2} D_1 f_0}{D} e^{-R_1 m_1(\sigma) - 3\pi i/4} d\sigma.$$

This form can be handled effectively by means of Debye's Method of Steepest Descent (see Copson, 1935). The contour is deformed continuously into the path of steepest descent through an appropriate saddle point of the real part of the exponent $m_1(\sigma)$. If some of the singularities lie outside this path, loops must be added connecting these singularities with the new curve. These loops begin and end on the path of steepest descent. With this provision, the new path of integration is equivalent to the old.

The appropriate saddle point in this case is $\sigma_0 = -k \sin\epsilon$ ($\alpha = ik \cos\epsilon$). The path of steepest descent is a curve which crosses the real axis of the σ-plane

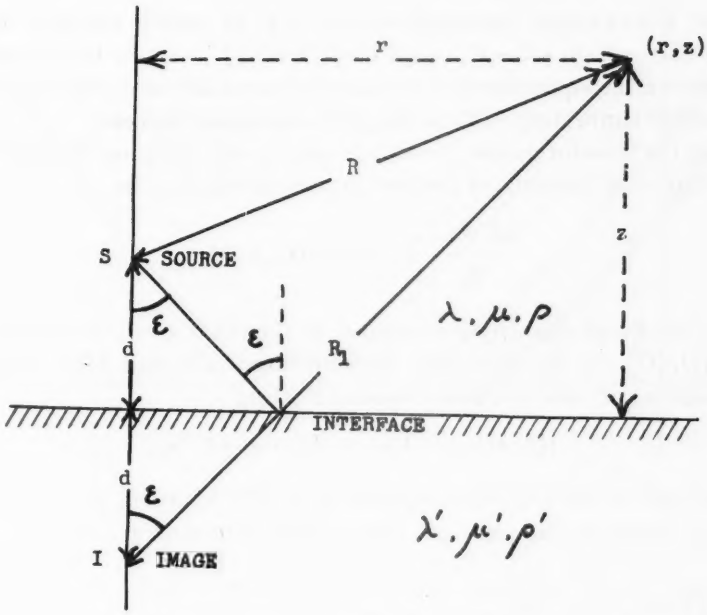

FIG. 2. Direct and reflected wave paths.

at points $-k \sin \epsilon$ and $-k/\sin \epsilon$, with asymptotes making angles of ϵ and $\pi - \epsilon$ with the real σ-axis (see Fig. 3). The singularities of the integrand are the branch points $-k$, $-h$, $-k'$, $-h'$ and the roots of $D=0$. Leaving out of consideration the poles, which are associated with Stoneley and pseudo-Rayleigh type waves along the boundary, the branch points are all distributed along the negative real axis, and depending upon the value of $\sin \epsilon$ lie inside or outside the path of steep-

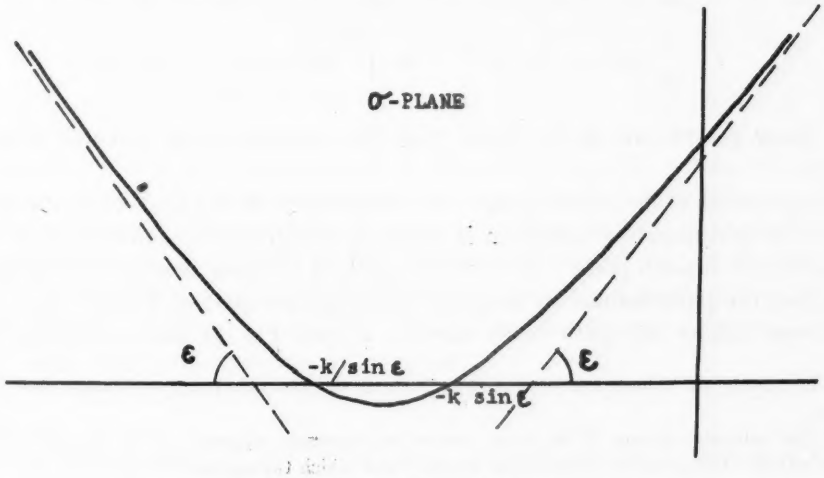

FIG. 3. Path of steepest descent.

est descent. For example, the condition that $-k'$ lie outside the path of steepest descent is that $-k \sin \epsilon < -k'$, or $\sin \epsilon > k'/k = V/V' = \sin i_1$. In this case, in order to preserve the equivalence of contours between the new and the old, a loop must be added connecting $-k'$ to the path of steepest descent.

Making the transformation, $\xi = m_1(\sigma) - m_1(\sigma_0)$ and applying Watson's Lemma, the contribution of the path of steepest descent is found to be

$$\frac{2k \cos \epsilon}{R_1} [f_0(\sigma) D_1/D]_{\sigma_0} e^{-ikR_1}$$

where the bracketed quantity is evaluated at the point $\sigma = \sigma_0 = -k \sin \epsilon$. The expression $[D_1/D]_{\sigma_0}$ is identical with the reflection coefficient for a P-wave incident at angle ϵ and reflected as a P-wave.[4] Putting

$$[D_1/D]_{\sigma_0} = A(\epsilon) = A'(\epsilon) + iA''(\epsilon),$$

it is found that $A''(\epsilon) = 0$, unless $\epsilon > \text{arc sin } V/V'$. Applying $\int_0^\infty \cdots e^{ikVt} dk$(real part) as an operator, the principal part of this wave emerges as

$$\begin{bmatrix} u_1 \\ w_1 \end{bmatrix} = \left[\frac{F_1(\epsilon)}{R_1} \left(A'(\epsilon) \frac{d}{dt} \{ p(t - R_1/V) \} - A''(\epsilon) \frac{d}{dt} \{ p_1(t - R_1/V) \} \right) \right] \begin{bmatrix} \sin \epsilon \\ \cos \epsilon \end{bmatrix}$$

where $F_1(\epsilon)$ is related to the amplitude of the incident P-wave as shown in equations (1) and where

$$\frac{d}{dt} \{ p(t - R_1/V) \} = \text{Rl} \int_0^\infty ikV p_1(k) e^{ikV(t - R_1/V)} dk$$

$$\frac{d}{dt} \{ p_1(t - R_1/V) \} = \text{Im} \int_0^\infty ikV p_1(k) e^{ikV(t - R_1/V)} dk.$$

The phase retardation R_1/V shows that this represents the reflected P-wave, P_1P_1.[5]

Contribution of the branch point $-k'$: It has been shown that when $\epsilon > \text{arc sin } V/V'$, an additional contribution is made by integration around the loop that connects the branch point $-k'$ with the path of steepest descent. Choosing for this loop the path defined by keeping the imaginary part of $[m_1(\sigma) - m_1(-k')]$ zero, and taking this path twice about $-k'$ (see Fig. 4) and connecting it to

[4] For numerical values, see, for example, Slichter and Gabriel (1933) or Muskat and Meres (1940).

[5] The individual letters, in the usual convention, represent segments of the ray path (real or hypothetical). The subscript refers to the velocity with which the segment is traversed; one, for velocities characteristic of the upper medium, and two, for those characteristic of the lower medium.

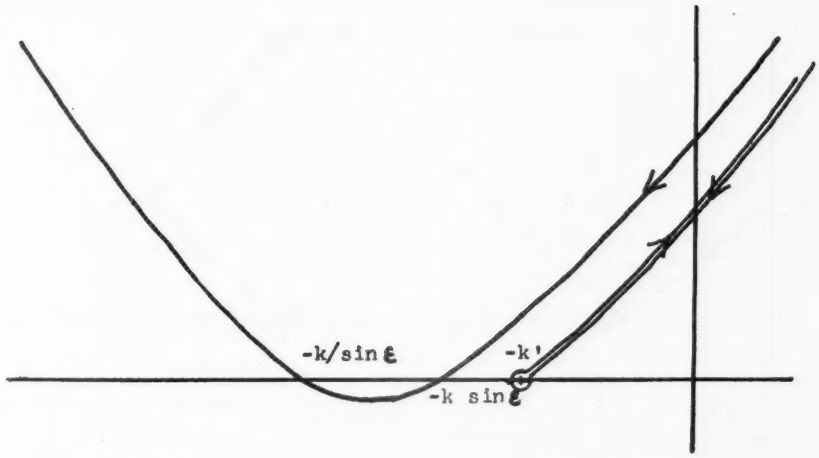

FIG. 4. Path of steepest descent with loop around the branch point $-k'$

the path of steepest descent at infinity, it is possible to change to the *real* variable $\xi = m_1(\sigma) - m_1(-k')$ and apply Watson's Lemma to the resulting integral. The principal part of this integration turns out to be

$$\begin{bmatrix} u_1(k') \\ w_1(k') \end{bmatrix} = \left[\frac{XF_1(i)p(\theta_1)}{r^{1/2}L_1^{3/2}}\right] \begin{bmatrix} \sin\ i_1 \\ \cos\ i_1 \end{bmatrix} \qquad (25a)$$

$$(25b)$$

where

$i_1 = \arcsin V/V'$, $L_1 = r - (z + d) \tan i_1$, $\theta_1 = t - [(z + d) \cos i_1]/V - r/V'$,

and

$$X = \left[\frac{i\sigma(P_1Q - Q_1P)}{Q^2 \cos i_1}\right]_{-k'}.$$

The phase retardation, $[(z+d) \cos i_1]/V + r/V'$, corresponds, as Muskat (1933) has shown, to the time taken for a wave to travel from the source to the point (r, z) by a path composed of the three segments SA, AB and BC shown in Figure 5, where SA is traversed with velocity V, AB with velocity V', and BC with velocity V. The vibration of the particle is longitudinal to the ray BC. This wave evidently corresponds to the head wave or "refracted wave" used in seismic prospecting. It may be denoted after Muskat (1933) by the three hypothetical segments of its path, namely $P_1P_2P_1$, where the subscripts refer to the velocities with which the segments are traversed.

The amplitude (equations 25a, 25b) of $P_1P_2P_1$ is the product of several factors:

1. $F_1(i_1)$ shows that the amplitude is a function of the amplitude of the *incident critical ray.*

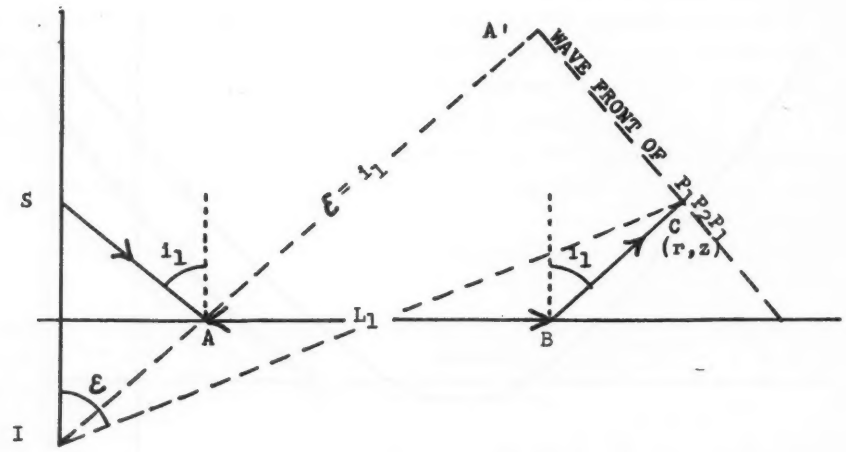

FIG. 5. Wave front of $P_1P_2P_1$.

2. $p(\theta_1)$, the time dependent factor, is related to the time dependent term of the incident radiation,[6] *viz.* $(d/dt)\{p(t-R/V)\}$ as a function is related to its time derivative. For the case of a small cylindrical source, $p(\theta_1)$ is identical with the impressed lateral force at the source, though retarded in phase by an amount corresponding to the travel time along its hypothetical path. (See Heelan, 1953.)

3. The presence in the denominator of $L_1 = AB$ (in Fig. 5), which is zero along the boundary AA' (or $\epsilon = i_1$) of the domain of existence of $P_1P_2P_1$, means that expressions (25a) and (25b) are not valid on AA'.

For points on $AA'(\epsilon = i_1 = \text{arc sin } V/V')$, the path of steepest descent passes through $-k'$, which is a singularity of the integrand, and the path of integration must then be indented by a small semi-circle so as to pass to the right of this point. The resulting integration gives an asymptotic series in descending *fourth* powers of R_1, the first term of which is identical with the principal term of P_1P_1.

The other branch points, $-h$ and $-h'$, also make their contributions to the value of the integral, but $-k$, which always lies within the path of steepest descent, contributes nothing. In the first case, if $-h < -k/\sin\epsilon$, i.e., $\epsilon > \text{arc sin } v/V$, a type of second-order boundary wave is obtained which we denote by $(S_1)_1$.[7] In the second case, if $-k \sin\epsilon < -h'$, i.e. $\epsilon > \text{arcsin } V/v'$, a head wave $P_1S_2P_1$ is obtained. If, on the other hand, $-k/\sin\epsilon > -h'$, i.e. $\epsilon > \text{arcsin } v'/V$, a type of second-order boundary wave, which we denote by $(S_2)_1$, is obtained. These results, with the corresponding results for the other integrals (15) to (24), are summarized in Tables I to IV that follow. The column headings denote the particular point in the σ-plane with which the particular wave form is associated.

Thus, beside the first order reflected and refracted waves, and the first order

[6] *Cf.* equation (1).

[7] Parentheses denote a boundary wave, i.e., a wave with amplitude diminishing exponentially with distance from the boundary.

TABLE I

WAVE SYSTEMS IN THE UPPER MEDIUM
P, SV COMPONENTS

	First Order Waves		Second Order Waves				
	Saddle Point	Roots $D=0$	$-k'$	$-k$	$-h'$	$-h$	Wave Type
u_1, w_1	P_1P_1	Stoneley and pseudo-Rayleigh Waves	$P_1P_2P_1$	—	$P_1S_2P_1$[a] $(S_2)_1$[b]	$(S_1)_1$	irrotational
u_2, w_2	S_1P_1		$S_1P_2P_1$	—	$S_1S_2P_1$[a] $S_1(S_2)$[b]	$(S_1)_2$	irrotational
u_3, w_3	P_1S_1		$P_1P_2S_1$	—	$P_1S_2S_1$[a] S_2S_1[b]	$(S_1)_3$	equivoluminal
u_4, w_4	S_1S_1		$S_1P_2S_1$	$S_1P_1S_1$	$S_1S_2S_1$	—	equivoluminal
SH COMPONENT							
v_1	S_1S_1				$S_1S_2S_1$	—	equivoluminal

TABLE II

DOMAINS OF EXISTENCE OF THE WAVES IN TABLE I
P, SV COMPONENTS

	Saddle Point	Roots $D=0$	$-k'$	$-k$	$-h'$	$-h$	
u_1, w_1	$z>0$	Determined by position of root	$\epsilon>i_1$	—	$\epsilon>i_3'$[a] $\epsilon>i_3$[b]	$\epsilon>i_5$	
u_2, w_2	$z>0$		$\epsilon_{21}>i_2$	—	$\epsilon_{21}>i_4$[a] $r/v'>$[b]	$r/v>$	$\dfrac{d}{v\cos\epsilon_{21}}+\dfrac{z}{v\cos\epsilon_{21}'}$
u_3, w_3	$z>0$		$\epsilon_{12}>i_1$	—	$\epsilon_{12}>i_3'$[a] $r/v'>$[b]	$r/v>$	$\dfrac{d}{V\cos\epsilon_{12}}+\dfrac{z}{v\cos\epsilon_{12}'}$
u_4, w_4	$z>0$		$\epsilon>i_2$	$\epsilon>i_5$	$\epsilon>i_4$	—	
SH COMPONENT							
v_1	$z>0$				$\epsilon>i_4'$	—	

[a] $v'>V$, i.e. $k>h'$.
[b] $v'<V$, i.e. $k<h'$.

TABLE III
WAVE SYSTEMS IN THE LOWER MEDIUM
P, SV COMPONENTS

	First Order Waves		Second Order Waves				
	Saddle Point	Roots $D=0$	$-k'$	$-k$	$-h'$	$-h$	Wave Type
u_1', w_1'	$P_1\underline{P}_2$	Stoneley and pseudo-Rayleigh Waves	—	$(P_1)_1$	$P_1(\underline{S}_2)^a$ $(\underline{S}_2)_1{}^b$	$(\underline{S}_1)_1$	irrotational
u_2', w_2'	$S_1\underline{P}_2$		—	$S_1(\underline{P}_1)_2$	$S_1(\underline{S}_2)$	$(\underline{S}_1)_2$	irrotational
u_3', w_3'	$P_1\underline{S}_2$		$P_1P_2\underline{S}_2$	$(\underline{P}_1)_3{}^a$	$(\underline{S}_2)_3{}^b$	$(\underline{S}_1)_3$	equivoluminal
u_4', w_4'	$S_1\underline{S}_2$		$S_1P_2\underline{S}_2$	$S_1(\underline{P}_1)_4{}^a$	$S_1P_1\underline{S}_2{}^b$	$(\underline{S}_2)_4$	equivoluminal
			SH COMPONENT				
v'	$S_1\underline{S}_2$				—	$(\underline{S}_1)$	equivoluminal

TABLE IV
DOMAINS OF EXISTENCE OF THE WAVES IN TABLE III
P, SV COMPONENTS

	Saddle Point	Roots $D=0$	$-k'$	$-k$	$-h'$	$-h$	
u_1', w_1'	$z<0$	Determined by position of root	—	$r/V>$	$r/v'>$	$r/v>$	$\frac{d}{V\cos\eta_{11}}-\frac{z}{V'\cos\eta_{11}'}$
u_2', w_2'	$z<0$		—	$r/V>$	$r/v'>$	$r/v>$	$\frac{d}{v\cos\eta_{21}}-\frac{z}{V'\cos\eta_{21}'}$
u_3', w_3'	$z<0$		$\eta_{12}>i_1$	$r/V>{}^a$	$r/v'>{}^b$	$r/v>$	$\frac{d}{V\cos\eta_{12}}-\frac{z}{v'\cos\eta_{12}'}$
u_4', w_4'	$z<0$		$\eta_{22}>i_2$	$r/V>{}^a$	$\eta_{22}>i_3{}^b$	$r/v>$	$\frac{d}{v\cos\eta_{22}}-\frac{z}{v'\cos\eta_{22}'}$
			SH COMPONENT				
v'	$z<0$				—	$r/v>$	$\frac{d}{v\cos\eta_{22}}-\frac{z}{v'\cos\eta_{22}'}$

[a] $v'>V$, i.e. $k>h'$. [b] $v'<V$, i.e. $k<h'$.

boundary (Stoneley and pseudo-Rayleigh) waves, there exist *twelve* second-order waves in each medium, of which *seven* (when $V>v'$) or *nine* (when $V<v'$) are head waves in the upper medium, and *two* (when $V>v'$) or *three* (when $V<v'$) are head waves in the lower medium.

Tables II and IV list the domains of existence of the corresponding waves in Tables I and III respectively. The angles ϵ, ϵ_{12}, ϵ_{21}, ϵ_{12}', ϵ_{21}' of Table II are defined for each point (r, z) by the following sets of equations:

$$r = (z + d) \tan \epsilon$$

$$r = z \tan \epsilon_{12}' + d \tan \epsilon_{12}; \qquad V/\sin \epsilon_{12} = v/\sin \epsilon_{12}'$$

$$r = z \tan \epsilon_{21}' + d \tan \epsilon_{21}; \qquad v/\sin \epsilon_{21} = V/\sin \epsilon_{21}'.$$

Referring to Figure 6, it is clear that ϵ, ϵ_{12}, ϵ_{21} are angles of incidence, while

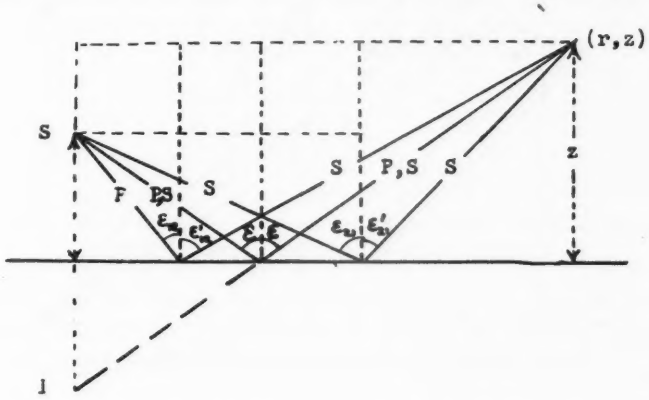

FIG. 6. Angles of incidence ϵ_{12} etc., and of reflection ϵ_{12}'.

$\epsilon' = \epsilon, \epsilon_{12}', \epsilon_{21}'$ are the corresponding angles of reflection of the four reflected waves that reach the point (r, z) from the source.

Similarly, the angles η_{11} etc., η_{11}' etc. of Table IV are defined for each point (r, z) by the following sets of equations:

$$r = -z \tan \eta_{11}' + d \tan \eta_{11}; \qquad V/\sin \eta_{11} = V'/\sin \eta_{11}'$$

$$r = -z \tan \eta_{22}' + d \tan \eta_{22}; \qquad v/\sin \eta_{22} = v'/\sin \eta_{22}'$$

$$r = -z \tan \eta_{12}' + d \tan \eta_{12}; \qquad V/\sin \eta_{12} = v'/\sin \eta_{12}'$$

$$r = -z \tan \eta_{21}' + d \tan \eta_{21}; \qquad v/\sin \eta_{21} = V'/\sin \eta_{21}'.$$

Referring to Figure 7, it is clear that the angles η_{11} etc. (unprimed) are angles of incidence, and η_{11}' etc. (primed) are angles of refraction of the various refracted waves that reach the point (r, z) from the source.

The critical (or pseudo-critical) angles i_1, i_2 etc. are defined as follows:

$$i_1 = \arcsin V/V', \qquad i_2 = v/V', \qquad i_3 = \arcsin v'/V \text{ (when } V > v'),$$
$$i_3' = \arcsin V/v' \text{ (when } V < v'), \qquad i_4 = \arcsin v/v',$$
$$i_5 = \arcsin v/V, \qquad i_6 = \arcsin v'/V'.$$

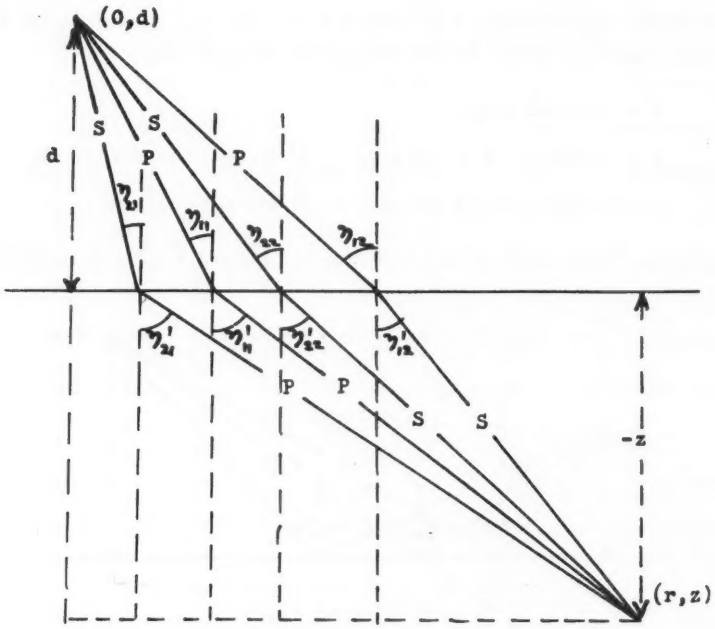

FIG. 7. Angles of incidence η_{12} etc., and of refraction η_{12}'.

STUDY OF A PARTICULAR HEAD-WAVE SYSTEM

In the preceding section, the complete set of first and second-order waves generated by the impact of a disturbance on a plane interface between two media, was obtained, and listed in two tables, with the domains of existence of these waves listed in two further tables. A careful scrutiny of the second-order waves, among which the various head waves are to be considered, shows that these are grouped together in systems which bear some relation to the critical angles of incidence of the impinging disturbance. Thus the head waves $P_1P_2P_1$ and $P_1P_2S_1$ in the upper medium, and $P_1P_2\underline{S}_2$ in the lower medium all involve the amplitude of the incident critical P-ray, all seem to start on the boundary at the point $r = d \tan i_1$,[8] and travel for a certain distance with velocity V' along the boundary *with a harmony of phase* before branching out into their respective media as waves of head-wave type (see Fig. 8).

The analytical expressions for the three head waves just mentioned are

[8] It will be remembered that i_1(=arcsin V/V') is the critical angle of incidence of the refracted P-wave.

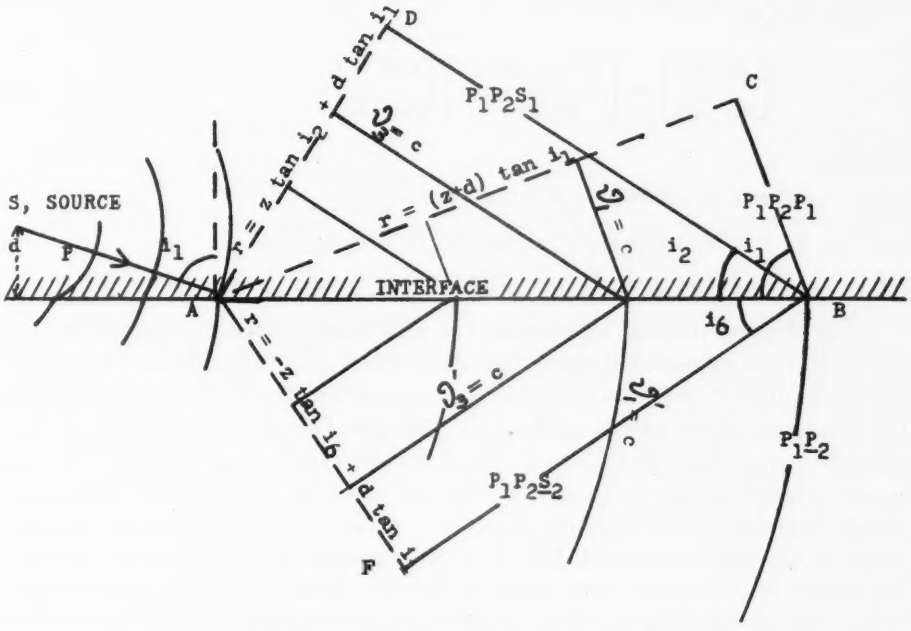

FIG. 8. Wave front diagram of the head wave system $P_1P_2P_1$, $P_1P_2S_1$, $P_1P_2S_2$ associated with the refracted P-wave.

grouped together below. Those for $P_1P_2P_1$ were given in the preceding section. The others can be derived by an application of the method described in that section to the integrals (u_3, w_3) and (u_3', w_3').[9]

For $P_1P_2P_1$:

$$\begin{bmatrix} u_1(k') \\ w_1(k') \end{bmatrix} = \begin{bmatrix} XF_1(i_1)p(\theta_1) \\ r^{1/2}L_1^{3/2} \end{bmatrix} \begin{bmatrix} \sin i_1 \\ \cos i_1 \end{bmatrix} \tag{26}$$

where

$$L_1 = r - (z + d) \tan i_1; \qquad \theta_1 = t - [(z + d) \cos i_1]/V - r/V';$$
$$X = [i\sigma(P_1Q - Q_1P)/Q^2 \cos i_1]_{-k'} \quad \text{and} \quad P_1, Q_1 \text{ etc.}$$

are algebraic expressions defined in equations (6) to (14).

For $P_1P_2S_1$:

$$\begin{bmatrix} u_3(k') \\ w_3(k') \end{bmatrix} = \begin{bmatrix} YF_1(i_1)p(\theta_3) \\ r^{1/2}L_3^{3/2} \end{bmatrix} \begin{bmatrix} -\cos i_2 \\ \sin i_2 \end{bmatrix} \tag{27}$$

where

$$L_3 = r - z \tan i_2 - d \tan i_1;$$
$$\theta_3 = t - [z \tan i_2]/v - [d \cos i_1]/V - r/V';$$
$$Y = [\sigma h \tan i_1(P_3Q - Q_3P)/Q^2]_{-k'} \quad \text{and} \quad i_2 = \arcsin v/V'.$$

[9] *Cf.* equations (17) and (22).

For $P_1P_2\underline{S}_2$:

$$\begin{bmatrix} u_3'(k') \\ w_3'(k') \end{bmatrix} = \begin{bmatrix} ZF_1(i_1)p(\theta_3') \\ r^{1/2}L_3'^{3/2} \end{bmatrix} \begin{bmatrix} \cos\ i_6 \\ \sin\ i_6 \end{bmatrix} \tag{28}$$

where

$$L_3' = r + z \tan i_6 - d \tan i_1;$$
$$\theta_3' = t + [z \cos i_6]/v' - [d \cos i_1]/V - r/V';$$
$$Z = [\sigma h' \tan i_1(P_3'Q - Q_3'P)/Q^2]_{-k'} \quad \text{and} \quad i_6 = \arcsin v'/V'.$$

It is of some interest to examine the relationship between these three head waves and the refracted P-wave, in view of the variety of opinions that exist as to the manner of generation of the head waves and the source of their energy. On this point, there are two schools of thought. One school (*cf.* Jeffreys, 1926; Muskat, 1933; Joos and Teltow, 1939; Scholte, 1946, 1947) regards the head waves as arising directly from the refracted wave by a process of "diffraction" at the boundary. The strongest objection to this view arises from the relatively large energy associated with $P_1P_2P_1$, a fact apparently repugnant to the physical notion of diffraction. The other school (*cf.* Macelwane, 1947; von Schmidt, 1936) regards the head waves as generated by a boundary wave of considerable energy in the lower medium, this wave itself owing its origin to the refracted P-wave at grazing incidence. This theory accounts quite satisfactorily for the observed strength of $P_1P_2P_1$. It introduces, however, a number of new and as yet unanswered questions regarding the nature and manner of origin of the boundary wave. A third opinion already disproved by the work of Jeffreys (1926), Muskat (1933), and Joos and Teltow (1939) was that the head wave was nothing other than a refracted P-wave deflected back in the direction from which it came by reason of a positive velocity gradient in the lower medium. While some of the energy in the head wave may, in fact, be obtained in this way, it has been shown that a positive velocity gradient is *not* a necessary condition for its existence.

In order to investigate the precise manner in which the head wave system comprising $P_1P_2P_1$, $P_1P_2S_1$ and $P_1P_2\underline{S}$ depends upon the refracted P-wave, it is necessary, first of all, to examine the behavior of that wave in the vicinity of the boundary. The integral yielding the amplitude of the refracted P-wave is[10]

$$u_1' = -\int_C \frac{\sigma f_0 D_1'}{D} H_1^{(1)}(\sigma r) e^{\alpha' z - \alpha d} d\sigma$$

$$w_1' = \int_C \frac{\alpha' f_0 D_1'}{D} H_0^{(1)}(\sigma r) e^{\alpha' z - \alpha d} d\sigma$$

where $\alpha = (\sigma^2 - k^2)^{1/2}$, $\alpha' = (\sigma^2 - k'^2)^{1/2}$, d is the distance of the source above the interface, and the functions D_1', D have been defined in the first section. Using the

[10] Equation (20).

method of steepest descent and carrying the asymptotic expansion to its second term, the amplitude of $P_1\underline{P}_2$ is found to be,

$$u_1' \simeq \left[\frac{\tan \eta_{11}}{V \sin \eta_{11}'}\right]\left[\frac{\sin \eta_{11}}{rU_1}\right]^{1/2} B(\eta_{11})F_1(\eta_{11})\left[\frac{d}{dt}\, p(\theta')\right] \sin \eta_{11}'$$
$$+ \left[\frac{\sin \eta_{11}}{rU_1}\right]^{1/2}\left[kE_1\left\{\frac{D_1'f_0}{D}\right\} + kE_2\frac{d}{d\sigma}\left\{\frac{D_1'f_0}{D}\right\}\right.$$
$$\left. + kE_3\frac{d^2}{d\sigma^2}\left\{\frac{D_1'f_0}{D}\right\}\right]_{\sigma_0} p_1(\theta') \qquad (29a)$$

$$w_1' \simeq -\left[\frac{\tan \eta_{11}}{V \sin \eta_{11}'}\right]\left[\frac{\sin \eta_{11}}{rU_1}\right]^{1/2} B(\eta_{11})F_1(\eta_{11})\left[\frac{d}{dt}\, p(\theta)\right] \cos \eta_{11}'$$
$$- i\left[\frac{\sin \eta_{11}}{rU_1}\right]^{1/2}\left[kE_1\left\{\frac{\alpha' D_1'f_0}{\sigma D}\right\} + kE_2\frac{d}{d\sigma}\left\{\frac{\alpha' D_1'f_0}{\sigma D}\right\}\right.$$
$$\left. + kE_3\frac{d^2}{d\sigma^2}\left\{\frac{\alpha' D_1'f_0}{\sigma D}\right\}\right]_{\sigma_0} p_1(\theta') \qquad (29b);$$

where

$$\theta' = t + z/V' \cos \eta_{11}' - d/V \cos \eta_{11},$$

$\sigma_0' = -k' \sin \eta_{11}' = -k \sin \eta_{11}$, with $\alpha_0' = ik' \cos \eta_{11}'$, and $\alpha_0 = ik \cos \eta_{11}$;

$$4ikU_1^4E_1 \sin^2 \eta_{11} = 21U_2 \sin^2 \eta_{11} + 3U_3U_1 \sin^2 \eta_{11} + 6U_2U_1^2 \sin \eta_{11} + U_1^3$$
$$iU_1^2E_2 = -3U_2 + U_1 \sin \eta_{11}$$
$$U_1E_3 = ik$$

with

$$U_1 = -kz/k' \cos^3 \eta_{11}' + d/\cos^3 \eta_{11}$$
$$U_2 = -\frac{k^2z \sin \eta_{11}'}{k'^2 \cos^5 \eta_{11}'} + \frac{d \sin \eta_{11}}{\cos^5 \eta_{11}}$$
$$U_3 = -\frac{k^3z(\cos^2 \eta_{11}' + 5 \sin^2 \eta_{11}')}{k'^3 \cos^7 \eta_{11}'} + \frac{d(\cos^2 \eta_{11} + 5 \sin^2 \eta_{11})}{\cos^7 \eta_{11}}$$

and $B(\eta_{11}) = [D_1'/D]_{\sigma_0'}$-refraction coefficient of P incident at angle η_{11} and transmitted as a P-wave, i.e., ratio of amplitudes of associated Knott functions, using the definition given by Slichter and Gabriel, (1933).[11]

To find the displacement produced by the refracted wave in the neighborhood of the boundary, beyond the cone of critical incidence, it is necessary to let $z \to \infty$, $\eta_{11}' \to \pi/2$, $\eta_{11} \to i_1 = \arcsin V/V'$, and $-z \tan \eta_{11}' \to [r - z \tan i_1] = \mathrm{L}$. Thus

[11] $B(\eta_{11})$ of the present notation corresponds to the A' used by Slichter and Gabriel; η_{11} is the angle of incidence.

$$U_1^{-1} \rightarrow [k' \cos^2 \eta_{11}']/kL \rightarrow 0.$$

The first term, consequently, in the expressions for u_1' and w_1' vanishes on the boundary and the character of the wave there is determined by the terms of the second-order. These reduce to

$$u_1' \simeq \frac{W_1 F_1(i_1) p(\theta)}{r^{1/2} L^{3/2}}$$

$$w_1' \simeq \frac{W_2 F_1(i_1) p(\theta)}{r^{1/2} L^{3/2}}$$

where

$$W_1 = ik' \tan i_1 [PD_1'/Q^2]_{-k'}$$
$$W_2 = \quad \tan i_1 [D_1'/Q]_{-k'}.$$

It should be noted that the vertical component of displacement is not zero. Thus, the particle displacement is not perfectly longitudinal to the path determined by geometrical optics, nor is the flow of energy along the geometrical ray.

It might be well to interrupt the discussion here to say a few words on the nature of first and second order waves. A localized source of seismic energy radiates a disturbance which is propagated outwards through a family of closed wave fronts that approach more and more closely to the spherical type with increasing distance from the source. The particle displacement in such a wave cannot be represented by a single term, as is the case with a plane wave, but it may be expanded in an asymptotic series in inverse powers of the distance from the source. When the first and predominant term is of the order of R^{-1} at infinity, the wave is called a first order wave.[12] It is clear from equations (29a) and (29b) that the refracted P-wave, $P_1\underline{P}_2$, is of this type. When the predominant term is of the order of R^{-2} at infinity the wave is called a second order wave. It will be seen without much difficulty that the waves specified by equations (26), (27), and (28) are of the latter type.

It can happen that the first order term of a wave like $P_1\underline{P}_2$ vanishes at certain points, or within a certain domain. In this case, the nature of the wave is governed by the second order term, and this may have properties different from those deducible from the first term alone. For example, we have seen that on the boundary, outside the cone of critical incidence, the particle displacement and energy flow in the refracted P-wave is governed by the second-order term, and that it is not directed *longitudinally* along the geometrical ray, which here lies parallel to the interface. The wave however, is still a dilatational wave, for its curl is zero.

[12] Considering only the term of the first order, such waves have properties closely resembling those of plane waves, obeying Snell's Law, diffusing energy normal to the wave front, and propagating energy to infinity.

Returning to our discussion of the relationship between the refracted P-wave and the three head waves, it can be seen that on the boundary ($z=0$), outside the cone of critical incidence (i.e. $r>d \tan i_1$),

$$\theta_1 = \theta_3 = \theta_3' = \theta' = t - [d \cos i_1]/V - r/V'.$$

The four waves $P_1\underline{P}_2$, $P_1P_2P_1$, $P_1P_2S_1$, and $P_1P_2\underline{S}_2$ are, consequently, in phase with one another on the boundary. A comparison of the displacement vectors shows moreover, that the vector sum of the displacements of the two waves in the upper medium, *viz.* $P_1P_2P_1$ and $P_1P_2S_1$, equals the vector sum of the displacements of the two waves in the lower medium, *viz.* $P_1\underline{P}_2$ and $P_1P_2\underline{S}_2$, where the four waves overlap on the boundary, i.e.

$$u_1(k') + u_3(k') = u_1' + u_3'(k')$$
$$w_1(k') + w_3(k') = w_1' + w_3'(k')$$

when $z=0$. Utilized in these results are the four identities:

$$\alpha P_1 + \sigma^2 P_3 - \sigma^2 P_3' + D_1' \equiv \alpha P$$
$$\alpha Q_1 + \sigma^2 Q_3 - \sigma^2 Q_3' \equiv \alpha Q$$
$$P_1 + \beta P_3 + \beta' P_3' \equiv -P$$
$$Q_1 + \beta Q_3 + \beta' Q_3' - D_1' \equiv -Q.$$

Similarly, the stresses exerted on the underside of the boundary by $P_1\underline{P}_2$ and $P_1P_2\underline{S}_2$ are continuous with those exerted by $P_1P_2P_1$ and $P_1P_2S_1$ on the upper side. Thus, from a physical point of view, the system of four waves, satisfying conditions of continuity of stress and displacement across the interface, represents a complete and independent dynamic system. No boundary wave appears, and none is required to satisfy the conditions of a real dynamic system propagated in the two media and linked dynamically across the boundary.

Origin of head wave energy.—Consider the flow of energy into a small box $AA'BB'$ (see Figure 9) set astride the boundary and bounded above and below by elements of area parallel to the boundary, and such that the dimensions of

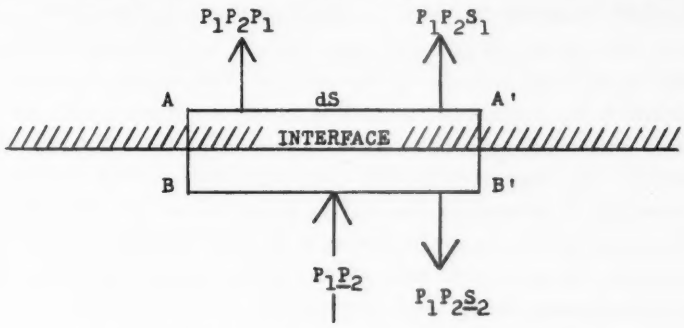

FIG. 9. Flow of energy into and out of box on boundary.

the sides AB and $A'B'$ are arbitrarily small. As no energy is created or destroyed within the box, the total energy leaving the box must equal the total energy entering it. It is found that the only energy entering the box is due to the vertical component of energy flow in $P_1\underline{P}_2$, and has the value (integrated over the duration of the disturbance),

$$-\frac{\mu' F_1(i_1)^2}{rL^3}\left[\frac{ih'^2 PD_1'^2}{Q^3}\right]_{-k'}\frac{\tan^2 i_1}{k'V'}\int_{-\infty}^{+\infty}\left[\frac{d}{dt}\,p(t)\right]^2 dtdS. \tag{30}$$

The total energy leaving the box in the waves $P_1P_2P_1$, $P_1P_2S_1$ and $P_1P_2S_2$ is

$$-\frac{F(i_1)^2}{rL^3}\left[\left\{i\mu L^2\alpha(P_1Q-Q_1P)^2 - i\mu h^2\sigma^2\beta(P_3Q-Q_3P)^2 - i\mu' h'^2\sigma^2\beta'(P_3'Q-Q_3'P)^2\right\}/Q^4\right]_{-k'}\frac{\tan^2 i_1}{k'V'}\int_{-\infty}^{+\infty}\left[\frac{d}{dt}\,p(t)\right]^2 dtdS. \tag{31}$$

With the help of the following identity,

$$\mu h^2\alpha(P_1Q-Q_1P)^2 - \mu h^2\sigma^2\beta(P_3Q-Q_3P)^2 - \mu' h'^2\sigma^2\beta'(P_3'Q-Q_3'P)^2 \equiv \mu' h'^2 PQD_1'^2,$$

it is seen immediately that expression (31) is identical with (30), the energy entering the box through $P_1\underline{P}_2$. We conclude therefore, that the energy of the three head waves $P_1P_2P_1$, $P_1P_2S_1$, and $P_1P_2S_2$ is derived solely and entirely from the refracted P-wave, not by virtue of the term which gives this wave its specific character at points located off the boundary (*viz.* the first order term), but by virtue of the term of the second order, a term, incidentally, which arises only when the wave fronts are curved.

We might enquire whether this process can legitimately be called *diffraction*. In the first place, the similarity between the mathematical formulation of the problem of light diffraction by a straight edge and its solution by Sommerfeld and others,[13] and the theory of head waves given here, is very striking and strongly urges the idea that the physical processes involved are analogous. There is one difference, however, that on account of the peculiar expression for the amplitudes of the head waves involving a factor in the denominator that can become very small, and because of the smaller frequencies involved, the head wave amplitude is not necessarily a small quantity compared with the amplitude of the incident radiation, as is the case with the diffracted light ray. Whether or not this destroys the argument for the close analogy between the two processes is largely a matter of personal opinion. We made use of the term head wave in this series of papers, partly to avoid having to make a decision on this matter, but for the most part, because this term seems better suited than any other to describe this phenomenon clearly and concretely.

[13] For an account of the problem and its solution, see Born, (1933, pp. 209–218).

It remains to compute the amplitudes from formulas (26), (27) and (28), and to compare these with the observed values. Table V lists the computed values for two of the cases considered by Slichter and Gabriel (1933) in their work on reflection coefficients. The task of comparing these with experimental values has not yet been undertaken.

TABLE V

AMPLITUDE COEFFICIENTS OF $P_1P_2P_1$, $P_1P_2S_1$, $P_1P_2S_2$ AND P_1P_2

	X	Y	Z	W_1	W_2
$\rho/\rho'=0.965$, $V/V'=v/v'=0.935$, Poisson's ratio$=0.25$, $i_1=69°$	17.0	1.3	0.0	17.3	7.2
$\rho/\rho'=0.8$, $V/V'=v/v'=0.75$, Poisson's ratio$=0.25$, $i_1=49°$	6.1	1.9	0.5	5.9	2.8

ACKNOWLEDGEMENT

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A CONTRIBUTION TO THE COMPUTATION OF THE "SECOND DERIVATIVE" FROM GRAVITY DATA*

OTTO ROSENBACH†

ABSTRACT

The theory and practical application of the second derivative method of gravity interpretation have been discussed by Elkins (1951) in a very interesting paper based partly on an earlier paper by Peters (1949). In this paper, Elkins shows how the second derivative may be computed at the center of a series of concentric circles using the arithmetic means of the gravity values, assumed to be continuous, around each circle.

A method is here proposed which does not use a continuum of gravity values but instead requires only a series development. The approximation formulas needed for the routine calculations can be derived by a method different from that of Elkins and the least squares adjustments he used can be dispensed with.

Two hypothetical examples using the formulas derived by the series method are given and the results are compared with those computed by Elkins' formula.

INTRODUCTION

The Bouguer Anomaly g as usually obtained in applied geophysics from gravity measurements is the vertical component of the gravity effect due to density anomalies in the earth's crust. The second derivative of g in the vertical direction, to be referred to as the "Second Derivative," is given by $\partial^2 g/\partial z^2$ (where the z axis points downward). Its importance arises from the fact that it tends to emphasize the local density anomalies rather than regional features and therefore a map of $\partial^2 g/\partial z^2$ values often gives a clearer picture than does the corresponding gravity map.

Elkins (1951) has discussed the computation of the second derivative from gravity data distributed over a surface in a very interesting recent article which is based partly on an earlier paper by Peters (1949). His results may be summarized as follows:

If the value of gravity $g(x, y, 0)$ is known everywhere in the horizontal plane $z=0$ (Fig. 1) and P is a point within the plane, then the arithmetic mean, $\bar{g}$ of g on a circle with radius r and P as center is generally defined by the function

$$\bar{g}(r) = \frac{1}{2\pi}\int_0^{2\pi} g(r, \phi, 0)d\phi. \tag{1}$$

The following relation exists between $\bar{g}(r)$ and the second derivative of g at P:

$$\left[\frac{\partial^2 g}{\partial z^2}\right]_P = -4\left[\frac{d\bar{g}(r)}{d(r^2)}\right]_{r=0}. \tag{2}$$

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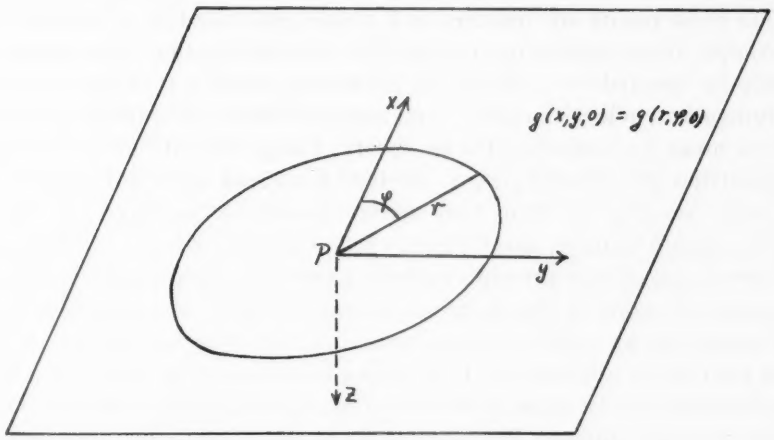

FIG. 1. Horizontal plane of gravity values and notation of coordinates.

Interpreting these results geometrically, it follows that on a plot of $\bar{g}(r)$ against r^2 in a cartesian coordinate system, four times the negative slope of $\bar{g}(r)$ at $r^2=0$ is equal to $\partial^2 g/\partial z^2$ at P.

Let us now consider how these relations can be used in practice. In practical applications, no continuous gravity data are available in the plane $z=0$ and g is known only from measurements at discrete points. Let us assume, as Elkins has

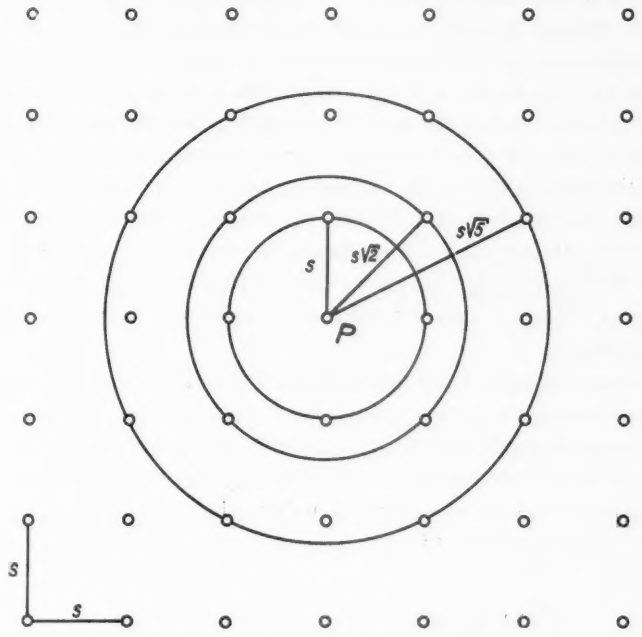

FIG. 2. Square grid and circles to compute the arithmetic mean of gravity values.

done, that these points are arranged in a square grid (see Fig. 2) without regard to the complications arising in practice from this assumption. The length of the sides may be denoted by s. Then, the arithmetic mean $\dot{g}(s)$ of the four gravity values lying on a circle with radius s and center P will be an approximation to the arithmetic mean $\bar{g}(s)$ introduced in his theory. Elkins also introduces the approximate quantities $\dot{g}(s\sqrt{2})$ and $\dot{g}(s\sqrt{5})$, derived from four and eight gravity values respectively (see Fig. 2). Thus four distinct points of the curve $\bar{g}(r)$ vs. r^2 are known by approximation, namely $\dot{g}(0)=\bar{g}(0)=g_P$, $\dot{g}(s)$, $\dot{g}(s\sqrt{2})$, and $\dot{g}(s\sqrt{5})$. It should now be possible in principle to draw a curve through these four points and to determine its slope at the origin graphically. Instead of a graphical method, Elkins introduces an equivalent numerical method that has proved to be very suitable for routine application. In so doing he replaces the curve by a straight line and determines the slope of the line in relation to the four discrete points by the method of least squares. This slope of the straight line replaces the differential quotient on the right side of equation (2). In this manner Elkins obtains, among others, the following standard formula for the second derivative:

$$\left[\frac{\partial^2 g}{\partial z^2}\right]_P = \frac{1}{62s^2}\left[44\dot{g}(0) + 16\dot{g}(s) - 12\dot{g}(s\sqrt{2}) - 48\dot{g}(s\sqrt{5})\right], \qquad (3)$$

attributing to the average value $\dot{g}(s\sqrt{5})$ only half the weight of the others.

For these computations essentially two methods of approximation have been employed: 1. The average value $\bar{g}(r)$ of a continuum of g-values has been replaced by the average value $\dot{g}(r)$ of a discrete number of g-values. 2. The curve $\dot{g}(r)$ has been replaced by a straight line using the method of least squares.

Elkins checked his formula in two ways: He first applied it to exact gravity data from simple anomalies for which the real values of the second derivative can be obtained, and compared his own values to the real ones. His second check consisted in applying his formula to measured gravity data and comparing the results thus obtained with those found by the graphical method mentioned above. These tests brought very satisfying results in the cases concerned. The figures published by Elkins demonstrating the application to measured gravity data are utterly amazing, although possibly he may have chosen specially selected examples for the purpose.

There is a more implicit reason why Elkins' formula stood up so well when applied to hypothetical examples. All of his examples were dealing with density anomalies lying at a considerable depth, thus implying relatively low fluctuations of the values of the second derivative. For density anomalies lying at higher levels the second derivative assumes extreme values that are not satisfactorily reproduced by the formula. Elkins himself mentions that his formula "cuts down peak values."

DEVELOPMENT OF SERIES EXPRESSIONS

For particular purposes, however, it seems desirable to use routine formulas which allow the computation of peak values of the second derivative within rea-

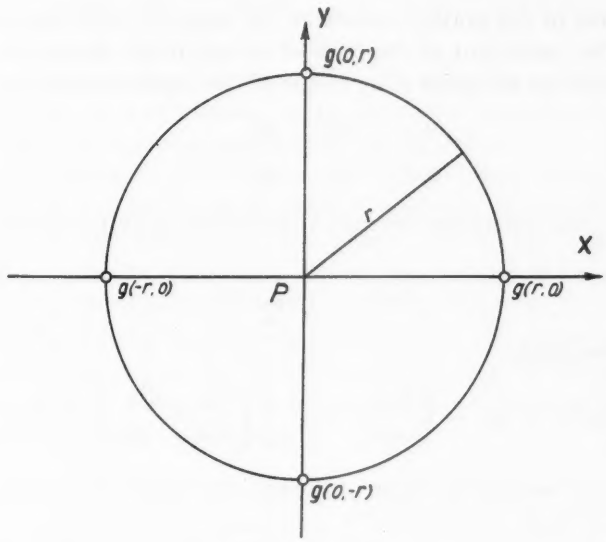

FIG. 3. Arrangement "A" of four points at distance r from P.

sonable limits. As a matter of fact, suitable expressions can be derived as shown below:

Let P again be a point of the plane $z=0$ for which the second derivative is to be determined (see Fig. 3). Gravity data are taken from points in the vicinity of P and developed in a series. Any coordinate system (x, y) with origin P is chosen in the plane $z=0$. The series for the gravity values, g, at the four points on the coordinate axes at a distance r from P are given by

$$g(r, 0) = g_P + \left(\frac{\partial g}{\partial x}\right)_P r + \frac{1}{2!}\left(\frac{\partial^2 g}{\partial x^2}\right)_P r^2 + \frac{1}{3!}\left(\frac{\partial^3 g}{\partial x^3}\right)_P r^3 + \cdots$$

$$g(0, r) = g_P + \left(\frac{\partial g}{\partial y}\right)_P r + \frac{1}{2!}\left(\frac{\partial^2 g}{\partial y^2}\right)_P r^2 + \frac{1}{3!}\left(\frac{\partial^3 g}{\partial y^3}\right)_P r^3 + \cdots$$

$$g(-r, 0) = g_P + \left(\frac{\partial g}{\partial x}\right)_P (-r) + \frac{1}{2!}\left(\frac{\partial^2 g}{\partial x^2}\right)_P r^2 + \frac{1}{3!}\left(\frac{\partial^3 g}{\partial x^3}\right)_P (-r)^3 + \cdots$$

$$g(0, -r) = g_P + \left(\frac{\partial g}{\partial y}\right)_P (-r) + \frac{1}{2!}\left(\frac{\partial^2 g}{\partial y^2}\right)_P r^2 + \frac{1}{3!}\left(\frac{\partial^3 g}{\partial y^3}\right)_P (-r)^3 + \cdots.$$

The sum of the four equations is given by

$$\sum_A g(r) = 4g_P + \left[\frac{\partial^2 g}{\partial x^2} + \frac{\partial^2 g}{\partial y^2}\right]_P r^2 + \frac{2}{4!}\left[\frac{\partial^4 g}{\partial x^4} + \frac{\partial^4 g}{\partial y^4}\right]_P r^4 + \cdots. \qquad (4)$$

The index A under the summation sign denotes here the specially selected position of the points in relation to the coordinate system. Because of the sym-

metrical position of the gravity values on the axes, the odd terms vanish in the summation. The coefficient of the term of second order represents the negative second derivative for the point P by virtue of the Laplace equation:

$$\frac{\partial^2 g}{\partial x^2} + \frac{\partial^2 g}{\partial y^2} + \frac{\partial^2 g}{\partial z^2} = 0. \tag{5}$$

By introducing the arithmetic mean of the four gravity values

$$\ddot{g}_A(r) = \frac{1}{4} \sum_A g(r),$$

equation (4) becomes:

$$4\ddot{g}_A(r) = 4g_P - \left(\frac{\partial^2 g}{\partial z^2}\right)_P r^2 + \frac{2}{4!}\left[\frac{\partial^4 g}{\partial x^4} + \frac{\partial^4 g}{\partial y^4}\right]_P r^4 + \cdots \tag{6}$$

where $\dot{g}_A(r)$ is the arithmetic mean of the gravity values at discrete points whose distance from P is r.

Solving the last equation for the second derivative, we obtain the series

$$\left(\frac{\partial^2 g}{\partial z^2}\right)_P = -4\frac{\dot{g}_A(r) - g_P}{r^2} + \frac{2}{4!}\left[\frac{\partial^4 g}{\partial x^4} + \frac{\partial^4 g}{\partial y^4}\right]_P r^2 + \cdots. \tag{7}$$

If we regard $\dot{g}_A(r)$ as a function of r^2, then the quotient in the first term of the

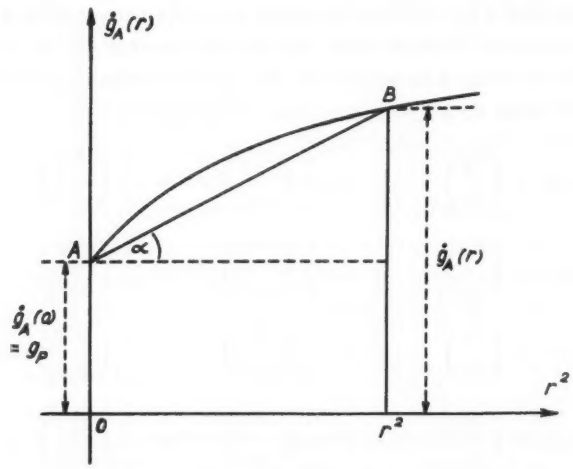

FIG. 4. $\dot{g}_A(r)$ as function of r^2.

series is a difference quotient. Geometrically, this represents the slope of the secant AB in Figure 4. Hence there exists the limit

$$\left(\frac{\partial^2 g}{\partial z^2}\right)_P = -4 \lim_{r \to 0} \frac{\ddot{g}_A(r) - g_P}{r^2} = -4\left[\frac{d\ddot{g}_A(r)}{d(r^2)}\right]_{r=0}. \tag{8}$$

A comparison of this relation with equation (2) derived by Elkins shows that in both cases the second derivative is represented by a differential quotient of an average value of gravity data for $r=0$. The difference lies in the fact that $\bar{g}(r)$ denotes the average of a continuum of gravity data, whereas $\bar{g}_A(r)$ stands for the average of four suitably chosen discrete gravity values.

The series of equation (7) shows that for suitable small distances r, the first term, that is to say the difference quotient, reasonably approximates the value of the second derivative. For practical purposes, however, the distance r should not be taken much smaller than 1 km. Otherwise, because of the inaccuracy of actual gravity data, the errors resulting from the multiplying factor $1/r^2$ would be too considerable. However, the second derivative can not generally be approximated exactly enough by the first term of the series for values of r as large as 1 km. This results in an impasse which can be overcome by taking further suitably chosen averages of gravity values.

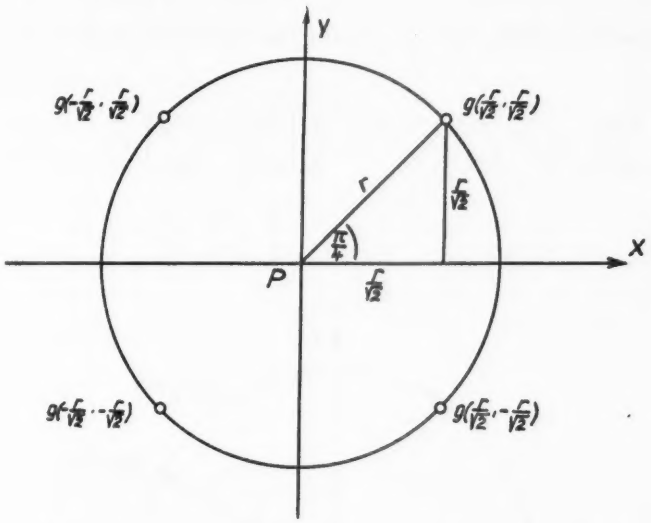

FIG. 5. Arrangement "*B*" of four points at distance r from P.

Such an average is obtained by the development in series of the gravity values at the points chosen in Figure 5, i.e.

$$g\left(\frac{r}{\sqrt{2}}, \frac{r}{\sqrt{2}}\right) = g_P + \left(\frac{\partial g}{\partial x}\right)_P \frac{r}{\sqrt{2}} + \left(\frac{\partial g}{\partial y}\right)_P \frac{r}{\sqrt{2}} + \frac{1}{2!}\left[\frac{\partial^2 g}{\partial x^2} + 2\frac{\partial^2 g}{\partial x \partial y} + \frac{\partial^2 g}{\partial y^2}\right]_P \frac{r^2}{2} + \cdots$$

$$g\left(-\frac{r}{\sqrt{2}}, \frac{r}{\sqrt{2}}\right) = g_P - \left(\frac{\partial g}{\partial x}\right)_P \frac{r}{\sqrt{2}} + \left(\frac{\partial g}{\partial y}\right)_P \frac{r}{\sqrt{2}} + \frac{1}{2!}\left[\frac{\partial^2 g}{\partial x^2} - 2\frac{\partial^2 g}{\partial x \partial y} + \frac{\partial^2 g}{\partial y^2}\right]_P \frac{r^2}{2} + \cdots$$

$$g\left(\frac{r}{\sqrt{2}}, -\frac{r}{\sqrt{2}}\right) = g_P + \left(\frac{\partial g}{\partial x}\right)_P \frac{r}{\sqrt{2}} - \left(\frac{\partial g}{\partial y}\right)_P \frac{r}{\sqrt{2}} + \frac{1}{2!}\left[\frac{\partial^2 g}{\partial x^2} - 2\frac{\partial^2 g}{\partial x \partial y} + \frac{\partial^2 g}{\partial y^2}\right]_P \frac{r^2}{2} + \cdots$$

$$g\left(-\frac{r}{\sqrt{2}}, -\frac{r}{\sqrt{2}}\right) = g_P - \left(\frac{\partial g}{\partial x}\right)_P \frac{r}{\sqrt{2}} - \left(\frac{\partial g}{\partial y}\right)_P \frac{r}{\sqrt{2}} + \frac{1}{2!}\left[\frac{\partial^2 g}{\partial x^2} + 2\frac{\partial^2 g}{\partial x \partial y} + \frac{\partial^2 g}{\partial y^2}\right]_P \frac{r^2}{2} + \cdots.$$

Of course the same coordinate system has been used as in Figure 3.

The sum of the four gravity values is therefore

$$\sum_B g(r) = 4g_P - \left(\frac{\partial^2 g}{\partial z^2}\right)_P r^2 + \frac{1}{4!}\left[\frac{\partial^4 g}{\partial x^4} + \frac{\partial^4 g}{\partial y^4}\right]_P r^4 + \frac{6}{4!}\left[\frac{\partial^4 g}{\partial x^2 \partial y^2}\right]_P r^4 + \cdots . \tag{9}$$

The index B under the summation sign again denotes the position of the gravity stations chosen in relation to the coordinate axes. Laplace's equation has been applied to the coefficient of the second order term.

As before we can now introduce the arithmetic mean,

$$\dot{g}_B(r) = \frac{1}{4}\sum_B g(r)$$

of the four gravity values, and we obtain the following relation for the second derivative:

$$\left(\frac{\partial^2 g}{\partial z^2}\right)_P = -4\frac{\dot{g}_B(r) - g_P}{r^2} + \frac{1}{4!}\left[\frac{\partial^4 g}{\partial x^4} + \frac{\partial^4 g}{\partial y^4}\right]_P r^2 + \frac{6}{4!}\left[\frac{\partial^4 g}{\partial x^2 \partial y^2}\right]_P r^2 + \cdots . \tag{10}$$

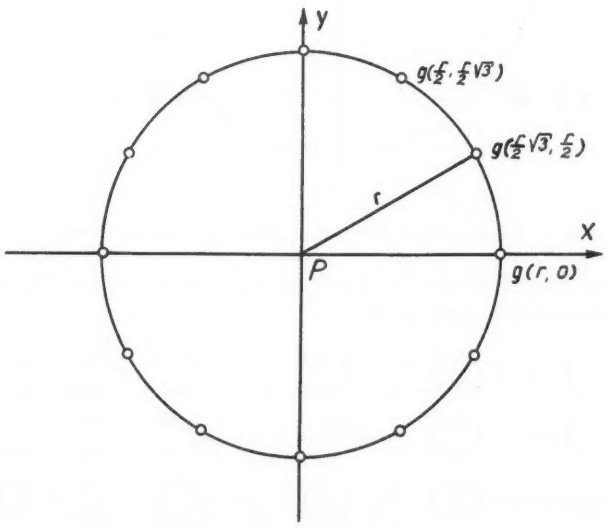

FIG. 6. Arrangement "C" of 12 points at distance r from P.

Any large number of symmetrically arranged points which lead only to terms of even order in the corresponding series can be found. Let us consider the arrangement C of 12 discrete points in Figure 6, using the same coordinate system as before. Summation of the corresponding series

$$g\left(\frac{r}{2}, \frac{r}{2}\sqrt{3}\right) = \cdots \quad g\left(\frac{r}{2}\sqrt{3}, \frac{r}{2}\right) \cdots \quad g(r, 0) = \cdots$$

$$g\left(-\frac{r}{2}, \frac{r}{2}\sqrt{3}\right) = \cdots \quad g\left(-\frac{r}{2}\sqrt{3}, \frac{r}{2}\right) = \cdots \quad g(0, r) = \cdots$$

$$g\left(-\frac{r}{2}, -\frac{r}{2}\sqrt{3}\right) = \cdots \quad g\left(-\frac{r}{2}\sqrt{3}, -\frac{r}{2}\right) = \cdots \quad g(-r, 0) = \cdots$$

$$g\left(\frac{r}{2}, -\frac{r}{2}\sqrt{3}\right) = \cdots \quad g\left(\frac{r}{2}\sqrt{3}, -\frac{r}{2}\right) = \cdots \quad g(0, -r) = \cdots$$

leads to the relation

$$\sum_C g(r) = 12 g_P - 3\left(\frac{\partial^2 g}{\partial z^2}\right)_P r^2 + \frac{9}{2\cdot 4!}\left[\frac{\partial^4 g}{\partial x^4} + \frac{\partial^4 g}{\partial y^4}\right]_P r^4 + \frac{9}{4!}\left[\frac{\partial^4 g}{\partial x^2 \partial y^2}\right]_P r^4 + \cdots . \tag{11}$$

Using the arithmetic mean

$$g_C(r) = \frac{1}{12}\sum_C g(r),$$

we obtain for the second derivative

$$\left(\frac{\partial^2 g}{\partial z^2}\right)_P = -4\frac{g_C(r) - g_P}{r^2} + \frac{3}{2\cdot 4!}\left[\frac{\partial^4 g}{\partial x^4} + \frac{\partial^4 g}{\partial y^4}\right]_P r^2 + \frac{3}{4!}\left[\frac{\partial^4 g}{\partial x^2 \partial y^2}\right]_P r^2 + \cdots . \tag{12}$$

We now substitute different values for r in the three second derivative series. In this way a specific point configuration is determined in the coordinate system (x, y) as shown, for example, in Figure 7. Here r has been made equal to s in arrangements A and C and $s/\sqrt{2}$ in arrangement B. Therefore, from the corresponding series of equations (7), (12), and (10), one obtains:

$$4\frac{g_A(s)-g_P}{s^2}=-\left(\frac{\partial^2 g}{\partial z^2}\right)_P+\frac{2s^2}{4!}\left[\frac{\partial^4 g}{\partial x^4}+\frac{\partial^4 g}{\partial y^4}\right]_P+0+\cdots$$

$$4\frac{g_C(s)-g_P}{s^2}=-\left(\frac{\partial^2 g}{\partial z^2}\right)_P+\frac{3s^2}{2\cdot 4!}\left[\frac{\partial^4 g}{\partial x^4}+\frac{\partial^4 g}{\partial y^4}\right]_P+\frac{3s^2}{4!}\left[\frac{\partial^4 g}{\partial x^2\partial y^2}\right]_P+\cdots \quad (13)$$

$$4\frac{g_B\left(\frac{s}{\sqrt{2}}\right)-g_P}{\frac{s^2}{2}}=-\left(\frac{\partial^2 g}{\partial z^2}\right)_P+\frac{s^2}{2\cdot 4!}\left[\frac{\partial^4 g}{\partial x^4}+\frac{\partial^4 g}{\partial y^4}\right]_P+\frac{3s^2}{4!}\left[\frac{\partial^4 g}{\partial x^2\partial y^2}\right]_P+\cdots .$$

All the quantities on the left sides of the above equations can be computed from the gravity data. On the right sides the series have been limited to terms up

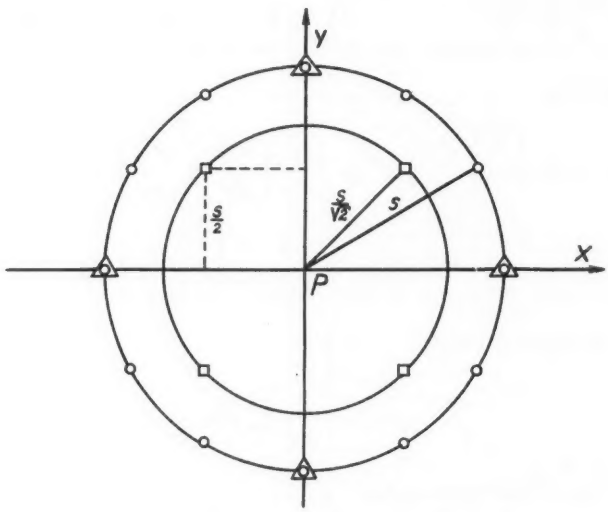

FIG. 7. Point configuration, composed of
△: arrangement "*A*" for $r=s$,
□: arrangement "*B*" for $r=s/\sqrt{2}$,
○: arrangement "*C*" for $r=s$.

to the fourth order. Thus a system of inhomogeneous linear equations with three unknown quantities has been obtained. The unknown quantities are the second derivative $(\partial^2 g/\partial z^2)_P$, and the quantities $[\partial^4 g/\partial x^4+\partial^4 g/\partial y^4]_P$ and $[\partial^4 g/\partial x^2\partial y^2]_P$. But only the unknown second derivative is of any interest in our problem. It can be evaluated by the well-known Cramer's rule. There is no need to calculate the values of the other two unknowns, but they should be taken into consideration as their coefficients are included in the computation of the second derivative with the aid of Cramer's rule. The solution of the system (13) is

$$\left(\frac{\partial^2 g}{\partial z^2}\right)_P \approx 2\cdot 4\,\frac{\dot{g}_C(s) - g_P}{s^2} - 4\,\frac{\dot{g}_A(s) - g_P}{s^2} - 2\cdot 4\,\frac{\dot{g}_B\left(\frac{s}{\sqrt{2}}\right) - g_P}{\frac{s^2}{2}}. \qquad (14)$$

As already stated, the three quotients on the right side of (14) can be interpreted as difference quotients. The negative quotients multiplied by four represent, in accordance with the above series, first approximations to the second derivative. Thus (14) is a linear combination of such first approximations. If all three have the *same* value, the second derivative naturally assumes this value also.

Equation (14) is too complicated however, for routine computation. The following formula tends to be more suitable for that purpose:

$$\left(\frac{\partial^2 g}{\partial z^2}\right)_P \approx \frac{1}{s^2}\left[12 g_P - \sum_A g(s) - 4\sum_B g\left(\frac{s}{\sqrt{2}}\right) + \frac{2}{3}\sum_C g(s)\right]. \qquad (15)$$

The expression (15) is obtained from (14) after introducing the sums of gravity values according to the relations

$$\dot{g}_A(s) = \frac{1}{4}\sum_A g(s); \qquad \dot{g}_B\left(\frac{s}{\sqrt{2}}\right) = \frac{1}{4}\sum_B g\left(\frac{s}{\sqrt{2}}\right); \quad \dot{g}_C(s) = \frac{1}{12}\sum_C g(s).$$

The derivation of formulas (14) and (15) involves only one approximation, namely the elimination of all terms after the third in the series of Equation (13). Elkins' method requires a greater degree of approximation.

Obviously other approximation formulas will be obtained if other appropriate point configurations are used as a basis for the calculation. In the arrangement of points A, B, C, given above, other values can be attributed to r. Furthermore other suitable arrangements of points can be employed, as, for example, an arrangement of eight points lying symmetrically with respect to the axes of the coordinate system and to the origin. It should be remembered, however, when selecting the point configuration, that only one specific point arrangement can be used (e.g. A). Should the same point arrangement be employed for two different values of r, then the second derivative is given by two linear equations with two unknowns which are determined by the two corresponding series of terms up to but not exceeding the fourth order. The addition of another point arrangement (e.g. B) leads to a system of three linear equations with three unknowns but the formula thus found for the second derivative will be identical with that found from the system of two equations, a result which should be easily understandable from a mathematical point of view.

The following remarks are added to insure a more complete understanding of the theory:

Three series have been used in the above exposition, since the clipped series

containing terms up to the fourth order resulted in three linear equations with three unknowns. Naturally, more than three series can be employed in theory, so that terms of a higher order than the fourth can be used. For example, using five series with terms up to sixth order results in general in five linear equations with five unknowns. In these equations, again, only the second derivative is of any interest in connection with our problem. In this case, the limitation on the use of the same point arrangements for different values of r must, of course, be modified. But for practical purposes this extended calculation will probably be of relatively small importance.

APPLICATION OF METHOD

In order to check the approximation method developed here, two hypothetical examples of so-called two-dimensional mass distributions have been selected for which the field of gravity as well as the field of the second derivative can be exactly calculated. The second derivative can be computed from gravity data with the help of Elkins' standard formula (Equation 3) as well as from Equation (15), derived here, so that a comparison can be made between the results of both approximation formulas and the true values of the second derivative.

In the first example the density anomaly is represented by a vertical fault

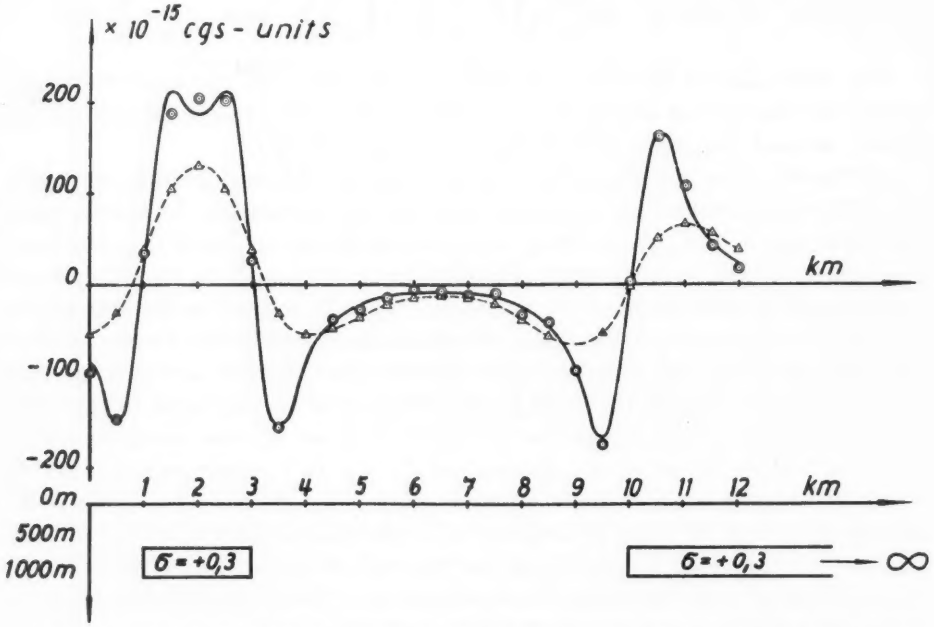

FIG. 8. Second derivative for a vertical fault and a rectangular block (two-dimensional structures).

——— : Curve of exact values.
---△--- : Approximate values computed from the standard formula (3) of Elkins.
◎ : Approximate values computed from formula (15).

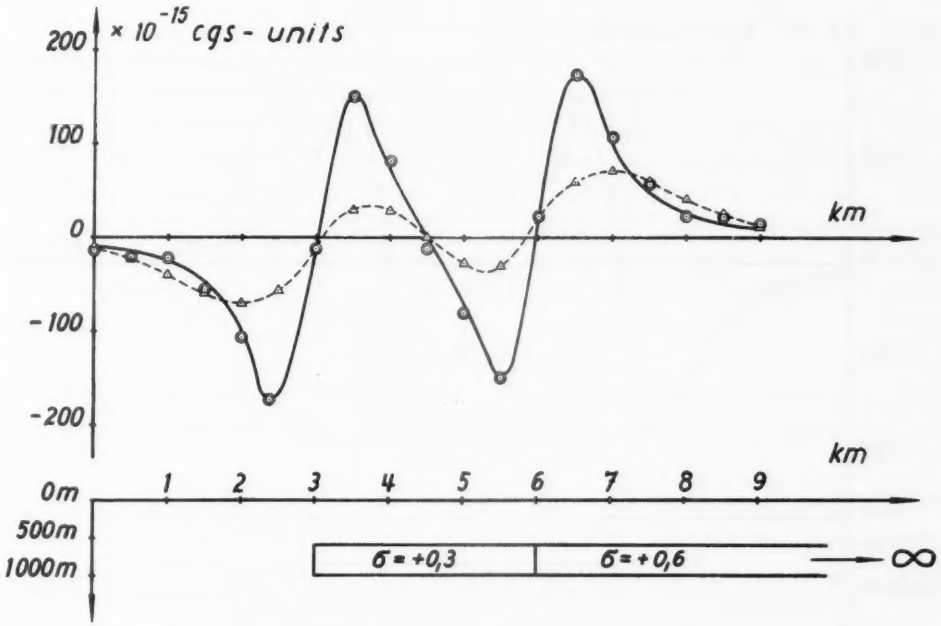

FIG. 9. Second derivative for the penetration of two vertical faults (numerical equivalent of step fault).

——— : Curve of exact values.
---△--- : Approximate values computed from the standard formula (3) of Elkins.
◎ : Approximate values computed from formula (15).

and a rectangular block (see Fig. 8). The gravity effect has been calculated for discrete points and a graph has been plotted along the profile accordingly. The application of the approximation formulas results in the values given in the figure.

The second example gives the density anomaly a rising from two vertical faults as shown in Figure 9. This form of mass distribution can be interpreted from a purely numerical point of view as a step fault. The results of the approximations are given in the figure.

A very interesting comparison may be made with the help of this example. As mentioned above, other approximation formulas can be derived along the lines of the method described here for suitably chosen point configurations. The configuration on which Elkins' standard formula is based is suitable for such a computation, yielding the relation,

$$\left(\frac{\partial^2 g}{\partial z^2}\right)_P \approx \frac{1}{24s^2}\left[96g_P - 18\sum g(s) - 8\sum g(s\sqrt{2}) + \sum g(s\sqrt{5})\right]. \qquad (16)$$

If we then apply this formula as well as Elkins' to a given field of gravity data, both formulas incorporate the same values of g. Using the gravity curve for the type of mass distribution in Figure 9 the formulas lead to the results shown

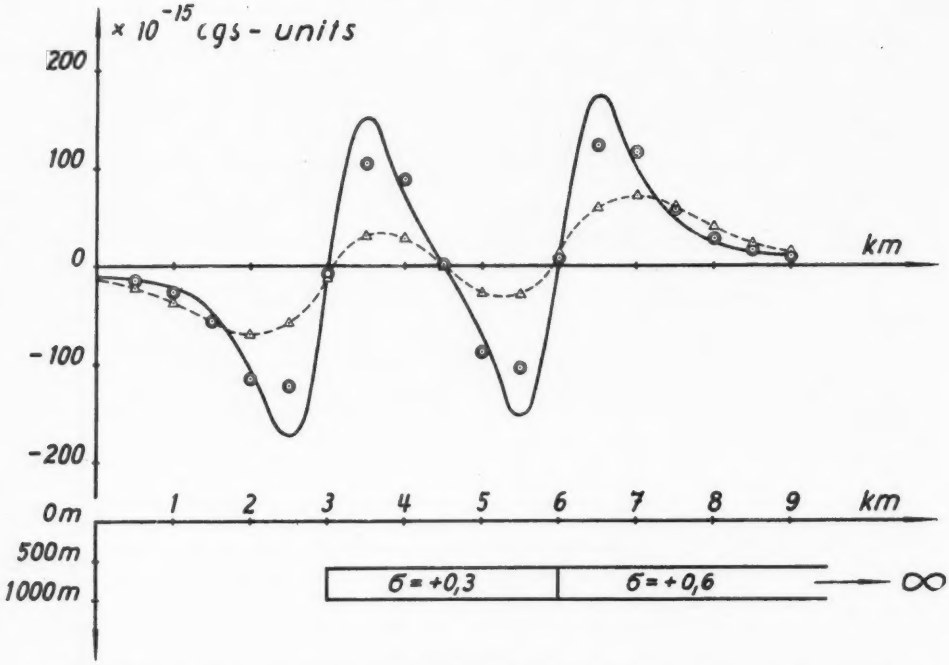

FIG. 10. Second derivative for the penetration of two vertical faults (numerical equivalent of step fault).

——— : Curve of exact values.

---△--- : Approximate values computed from the standard formula (3) of Elkins.

◎ : Approximate values computed from formula (16).

Note: Both formulas (3) and (16) are based on the same point configuration and therefore incorporate the same gravity values for the computation of the approximate values of the second derivative.

in Figure 10. From these results we may say that for this particular problem the approximation process adopted in the present investigation seems to be more adequate than the one introduced by Elkins.

Figures 8, 9, and 10 show that it is possible, along the lines described, to obtain approximation formulas for the second derivative that lend themselves to the calculation of peak values. But we should add that in both examples the approximation formulas have been applied for $s = 1$ km and for the same profile points at a distance of $\frac{1}{2}$ km. We shall not discuss here whether these relatively short distances between the points necessitate in practice a narrow grid of gravity stations. Correspondingly, the question of how to attain a suitable exactness of those gravity values in the summations involving stations different from the intersection points of a square grid, will remain open. These questions, which are very important from the standpoint of practical application, will be taken up in a later investigation.

The theory here developed for determining second derivatives from gravity

data can also be applied as a theoretical foundation for the Average Value Method of determining regional gravity (Griffin, 1949; Jakosky, 1950, pp. 416–420). This subject will be treated in a separate publication.

As mentioned at the beginning, Elkins has developed the theoretical part of his gravity investigation on the basis of a publication on magnetic interpretation by Peters (1949). The results found by Elkins for the case of gravity data could be improved by means of a more adequate mathematical method such as is described in the present paper. Of course this method may also be applied to magnetic data, which means, conversely, that Peters' results can be improved in the same way.

ACKNOWLEDGMENTS

The author wishes to thank the PRAKLA, Gesellschaft für praktische Lagerstaettenforschung G.m.b.H., Hannover, for kindly giving him permission to publish this paper.

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DISCUSSION BY LEO J. PETERS† AND THOMAS A. ELKINS†

We would like to call attention to a point of considerable practical importance which is neglected in this interesting and ingenious paper on the computation of the second derivative. This is the fact that gravity field data inevitably contain errors so that the second derivative values computed by coefficients from this gravity data also will contain errors, which may be of such magnitude as to mask the real effects caused by geologic structure, the finding of which was the purpose of the gravity survey. Consequently, extreme accuracy of a second derivative coefficient set is undesirable for use on practical data when it necessitates a high value of probable error as in the case of the sets presented by Dr. Rosenbach. It has been our practice to tolerate the blunting of peak values in order to avoid a high "noise" level which would mask the anomalies of interest, and this point was taken into consideration in the preparation of our second derivative formula mentioned in the next paragraph.

It is easy to predict the error behavior of a second derivative coefficient set for it is merely a weighted sum of the gravity values. Consequently, if each gravity value is subject to a random error of standard deviation E, the standard deviation of the second derivative value is merely E times the square root of the sum of the squares of the individual coefficients of the gravity values. Thus for

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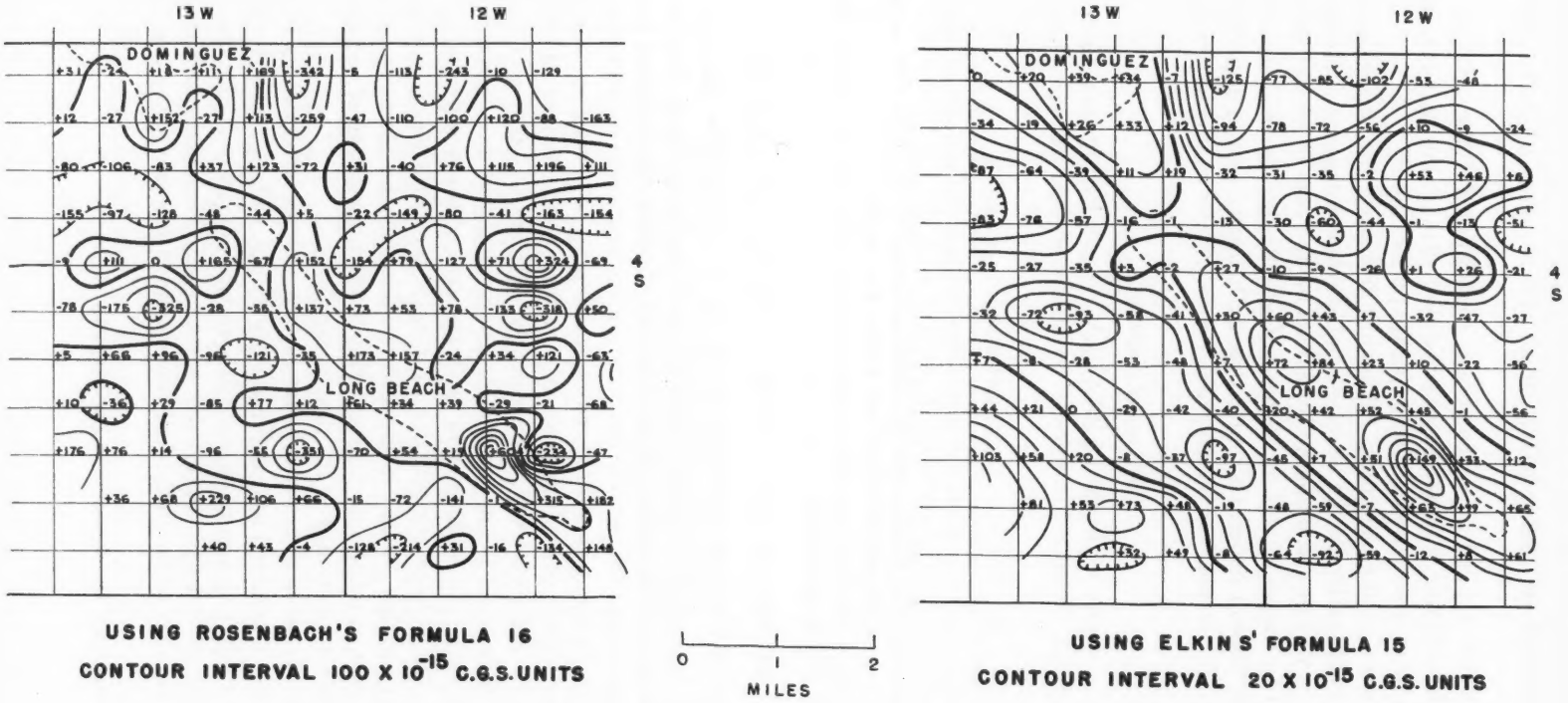


FIG. A OF DISCUSSION: Second derivative contours for portion of Los Angeles Basin, California.

Rosenbach's formula (16) the standard deviation of a second derivative value is $4.3253\ E/S^2$, while for Elkins' formula (15),[1] which uses the same grid configuration and is listed as equation (3) in Rosenbach's paper, the standard deviation is only $0.7775\ E/S^2$. Here S is the unit grid spacing.

As an example, we offer Figure A. This shows the second derivative contours, computed by the two formulas mentioned above, for a portion of an observed gravity picture of the Los Angeles basin recently published.[1] Because of the high probable error of the Rosenbach formula it was impractical to use the same contour interval (20×10^{-15} c.g.s. units) for it as for the other; instead a contour interval five times as great (100×10^{-15} c.g.s. units) was used. Even in spite of this, its more erratic and "noisy" nature is evident. It is literally a case of not being able to see the forest because of the trees.

REPLY BY DR. ROSENBACH

The errors involved in the second derivative coefficient sets of Elkins and myself are not as divergent as one would expect from the respective standard deviation figures, $0.7775\ E/s^2$ and $4.3253\ E/s^2$, given by the authors of the discussion.

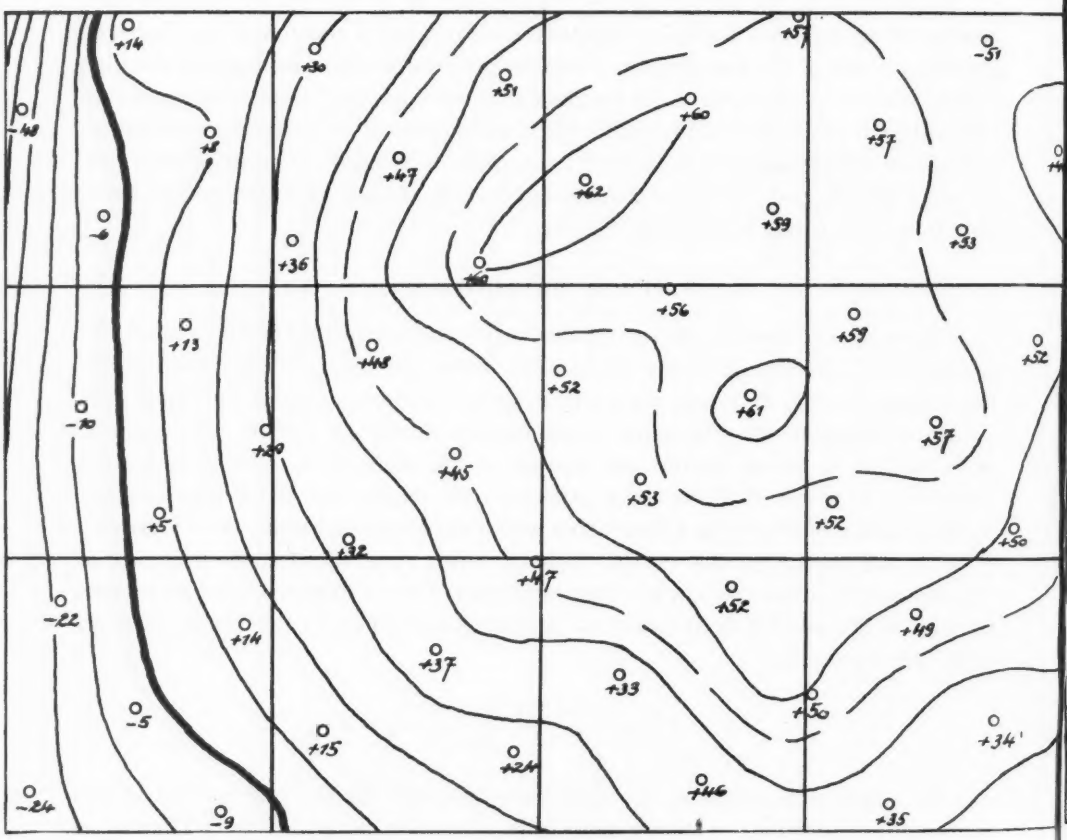
Both formulae use the same point configurations on circles, with radii s, $s\sqrt{2}$, and $s\sqrt{5}$, whose centers are located at the point P, at which the second derivative is required. However a close analysis shows that the Elkins formula yields a value of the second derivative which depends essentially on the gravity g^P at P and on the gravity on the circle of radius $s\sqrt{5}$, whereas the influence of gravity on the other two circles is unimportant. This is demonstrated by a comparison of the second derivatives as calculated according to the Elkins formula with the expression

$$D = -4\frac{\bar{g}(s\sqrt{5}) - \bar{g}(0)}{5s^2}$$

i.e. the negative fourfold of the difference quotient for the interval $5s^2$ in the rectangular coordinate system with r^2 as abscissa and $\bar{g}(r)$ as ordinate. The values compared here differ only slightly from each other, as can easily be shown by means of theoretical as well as practical examples.

On the other hand, the values of the second derivative as given by my formula are influenced least by the gravity on the circle of radius $s\sqrt{5}$ and depend to a greater extent on the gravity on the circle of radius s. This is immediately verified by a glance at the absolute values of the corresponding coefficients. It follows that if the second derivative according to my formula is to be determined with the same gravity values used to obtain it according to the Elkins formula a grid spacing of at least $2s$ instead of s must be chosen. And thus the standard deviation of a second derivative value becomes $4.3253\ E/4s^2$, which is thus of

[1] See: The second derivative method of gravity interpretation, by Thomas A. Elkins, *Geophysics*, Vol. 16, pp. 29–50 (1951).



Second Derivative according to the Elkins Formula.
Contour Interval: —— 10×10^{-15} cgs
— — 5×10^{-15} cgs

SCALE:

FIG. B of Discussion: Second Derivative Contours for Portion of Worms Area, Germany. (Couring for computation of second derivative: 1 km.

Second Derivative according to the Rosenbach Formula.
Contour Interval: —— 100×10^{-15} cgs
— — 20×10^{-15} cgs

tesy of Gewerkschaft Elwerath, Hannover.) Grid spacing of gravimeter stations: 1/2 km. Grid spac-

the same order of magnitude as that obtained by the Elkins method. If, on the other hand, the second derivative according to the Elkins formula is to be influenced to the greatest extent by gravity on the circle of radius s, a grid-spacing $s/\sqrt{5}$ would have to be chosen. The standard deviation would then become $0.7775 \times 5E/s^2$, which is of the same order of magnitude as the standard deviation according to my formula for grid-spacing s.

I am certainly aware of the sensitivity to errors in my formula. Thus in practical applications I have laid great stress on an extremely careful process for interpolating the actual gravity data on the corners of a quadratic grid (partly according to a successive process as yet unpublished). I do not know whether the same care was exercised in the determination of the second derivative according to my formula in the test area of the Los Angeles Basin where the gravimeter stations did *not* form an exactly square grid (cf. Elkins, 1951, *Geophysics*, Vol. 16, p. 47, fig. 15). According to my experience this does not appear to be the case in view of the considerably divergent values of $+604$ and -234, for instance, in the S.E. corner of the test area. This would be quite understandable, since the Elkins formula does not require such a high degree of accuracy. I would be obliged to Messrs. Peters and Elkins if they would let me have the observed gravity anomalies of the test area so that I can apply my formula according to my own methods of calculation.

The application of my formula involves more labor. This is justified for instance by the fact that its results allow the recognition of smaller structures which cannot be deduced by means of the Elkins formula. An example of this was given at the Hannover meeting of the European Association of Exploration Geophysicists (EAEG) in December, 1952. Since this will be published shortly I am not in a position to present the corresponding figures here. But by kind permission of Dr. G. Brinckmeier, Gewerkschaft Elwerath, Hannover, Germany, I am able to offer the attached examples. (See Figure B of Discussion). The relative maximum of the second derivative according to my formula is caused by a structure known from seismic work and drilling. Obviously, the second derivative according to the Elkins formula does not permit one to recognize this structure. There are further similar examples in the same area.

RESIDUAL ANOMALIES AND DEPTH ESTIMATION*

SVEND SAXOV† AND KURT NYGAARD†

ABSTRACT

The residual gravity anomaly at a point is defined as the difference between the average anomalies along two concentric circles whose center is at the point, divided by the difference between the two radii or

$$R(g) = -\frac{\bar{g}(r_1) - \bar{g}(r_2)}{r_1 - r_2}.$$

It is shown that the residual anomalies previously determined by the average circle or the average polygon method (Griffin, 1949) are included in the present definition. The second vertical derivative of g and, to some extent, the fourth vertical derivative of g (Peters, 1949) are also included.

The relation between the residual anomalies and the depth of the subterranean masses is examined. It has been pointed out that the gravitational effect originating from a body with mass m is clearly apparent when the center of mass of the body has the depth $z=2r=r_1+r_2$. The influence from masses at a greater or lesser depth is almost eliminated.

By avoiding the use of the center point in the figuring of the residual anomalies the influence of random errors is minimized.

INTRODUCTION

Depth estimation is of primary concern in gravity prospecting and in other geophysical work. It is the purpose of this paper to show how residual anomalies can be used to estimate the depth of subterranean masses.

Although there has been a large body of literature on residual anomalies (Fisher, 1941; Hughes, 1942; Skeels, 1942; Kogbetliantz, 1944, 1945, and 1946; Griffin, 1949; Peters, 1949; Skeels and Watson, 1949; Agocs, 1951), the relationship between these anomalies and the depth of their source has generally been omitted in the published discussions.

Estimation of the subterranean mass which causes a gravitational effect is also of concern, particularly in mining prospecting (Jung, 1937; Tsuboi and Fuchida, 1937; Hammer, 1945; Bullard and Cooper, 1948); such mass estimation is often closely related to depth estimation.

For many years it was customary in the interpretation of gravity data to use such arbitrary procedures as the profile method or the "smoothed-contour" method. Recently, more accurate methods have been worked out and it is now possible, by use of mathematical calculations, to remove the regional effect, which is the force resulting from masses far away from the area under consideration or, more usually, from masses at very great depths. If Z is the regional anomaly, R is the residual anomaly, and G is the reduced Bouguer gravity anomaly, we may define R by the following equation:

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$$R = G - Z. \tag{1}$$

We may further define the regional anomaly as the average of the Bouguer anomalies along a circle of radius r, the center being at the point of computation. The residual anomaly is then the difference between the Bouguer anomaly at the point and the average anomaly around the circle; consequently equation (1) will take the form

$$R = G - \frac{1}{2\pi}\int_0^{2\pi} g(r, \theta)d\theta. \tag{2}$$

In practical computation it is convenient to replace the circle with a polygon (Griffin, 1949) and equation (2) becomes

$$R = G - \frac{1}{n}\left[g_1(r) + g_2(r) + \cdots + g_n(r)\right]. \tag{3}$$

In this method, any random error in the value of gravity observed at the center of the circle or polygon will be transferred virtually in full to the computed value of the residual anomaly since errors in the gravity values observed along the circle or polygon will tend to cancel out in the averaging.

Another theory making use of the derivatives $\partial g/\partial z$, $\partial^2 g/\partial z^2$, and $\partial^4 g/\partial z^4$ has been developed (Peters, 1949; Elkins, 1951). The average gravity value $\bar{g}(r)$ along a circle with radius r has been given the form

$$\bar{g}(r) = b_0 + b_2 r^2 + b_4 r^4 + \cdots \tag{4}$$

and adequate formulas for the derivatives have been set up. From them it is possible to reduce the gravity data in a limited time and without too much labor. We will refer to the residual anomalies defined in (2), (3), and (4) later on in this paper.

Recently another residual method called the "least squares residual anomaly determination" has been introduced (Agocs, 1951). By use of least squares a plane is determined and the residual anomaly is defined as the difference between the observed Bouguer anomaly and the corresponding value on the plane. It is easily seen that this method is dependent on the length and the width of the plane and it is not possible to obtain a direct correlation between the residual anomalies and the depth of the subterranean masses.

Finally, we want to mention the procedure outlined by Kogbetliantz (1944, 1945, and 1946) for interpreting maps of potential (magnetic and gravitational) anomalies. His method is general and is based upon the use of average values only. It yields quantitative interpretations and does not depend on the existence of well-pronounced maxima or minima. It is applicable equally well to small anomalies. However, the method is expressed in a mathematical form that does not seem to be suited for economic applications.

The relationship between the residual anomalies and the depth to the sub-

terranean masses has not been solved in any of the theories mentioned above. It should be said that Peters (1949) deals with the estimation of depth but not in relation to the second or fourth vertical derivative. He bases his estimation procedure on practical experience and there is no doubt that the depths obtained in this way are accurate within some 80%.

Fisher (1941) has shown that the first and the second vertical derivatives of g can be used to estimate the depth to a subterranean mass. If h and h_1 are the minimum and the maximum depths, respectively, to the surface of the mass, it is pointed out that

$$\left.\begin{aligned} h_1 - h &\geqq \frac{g}{2\pi\sigma\gamma} \\ \log\frac{h_1}{h} &\geqq \frac{\dfrac{\partial g}{\partial z}}{2\sigma\gamma} \\ \frac{1}{h} - \frac{1}{h_1} &\geqq \frac{\dfrac{\partial^2 g}{\partial z^2}}{2\cdot 7\cdot 5\cdot\gamma} \quad \text{or} \quad h < \frac{2\cdot 7\cdot 6\cdot\gamma}{\dfrac{\partial^2 g}{\partial z^2}} \end{aligned}\right\} \tag{5}$$

where γ is the universal gravitational constant and σ is density.

Bullard and Cooper (1948) have pointed out that the effect of the potential anomaly of a subterranean mass is dependent on the depth and that the effect cannot be registered when the mass is below a limiting depth. For a horizontal sheet of thickness h at depth z, with the density varying horizontally (in the x direction) as $\sigma \cos px$, we get the inequality

$$z < p^{-1} \log \frac{2\pi\gamma\sigma_m h}{g} \tag{6}$$

where $g = 2\pi\gamma\sigma e^{-pz}$. If it is not possible to express g in the form $A \cos px$, one may transform (6) with the help of a Fourier series ($p = \pi/x_m$) and the inequality is written

$$z < \pi^{-1} x_m \log \frac{4\pi\gamma\sigma_m h}{g_m} . \tag{7}$$

If the same argument is used for a mass of indefinite thickness, the following inequality is found:

$$z < \pi^{-1} x_m \log \frac{4\pi\gamma\sigma_m x_m}{g_m} . \tag{8}$$

Formulas (6), (7), and (8) have been used in computation of deep-seated masses such as the Alps, but they are hardly suitable for practical purposes.

If we want to tackle the problem of estimating the depth to a subterranean mass, we would prefer to use two concentric circles centered at a point having the Bouguer gravity anomaly g and it is only the values along the two circles which are to be examined. In this way it is possible to avoid the influence of the random error at the center point while the errors of the average circle values are normally eliminated because of the laws of error distribution. This method makes use of several of the residual anomaly theories just described and it has the advantage of being applicable for practical purposes.

EXPRESSIONS FOR RESIDUAL ANOMALY

If $\bar{g}(r)$ is the average value of the Bouguer anomalies $g(r, \theta)$ around a circle of radius r the following expression may be written:

$$\bar{g}(r) = \frac{1}{2\pi}\int_0^{2\pi} g(r, \theta)d\theta. \tag{9}$$

The residual anomaly $R(g)$ is defined as

$$R(g) = a_0\bar{g}(r_0) + a_1\bar{g}(r_1) + a_2\bar{g}(r_2) + \cdots + a_n\bar{g}(r_n) = \sum_{p=0}^{n} a_p\bar{g}(r_p). \tag{10}$$

Put into practice, this formula can only be used for a limited number of radii and for a discrete number of points along each circle $\bar{g}(r_p)$. Furthermore the values are obtained from the observational anomalies $g(r_p, \theta)$ which are influenced by random errors.

In general, therefore, the residual anomaly can better be defined as

$$R(g) = k\bar{g}'(r) \tag{11}$$

where k is a constant depending on the value of r. Equation (11) is valid for the proper values of k and r which are independent of the function g.

If the anomaly at the center is denoted as $g(o)$,

$$\left.\begin{aligned} \bar{g}(r_1) &= \bar{g}(o) + \frac{r_1^2}{2!}\bar{g}''(o) + \frac{r_1^4}{4!}\bar{g}^{IV}(o) + \cdots \\ \bar{g}(r_2) &= \bar{g}(o) + \frac{r_2^2}{2!}\bar{g}''(o) + \frac{r_2^4}{4!}\bar{g}^{IV}(o) + \cdots \\ &\cdots\cdots\cdots\cdots\cdots\cdots \end{aligned}\right\}. \tag{12}$$

Inserting (12) in (10) we get

$$R(g) = \bar{g}(o)\sum_{p=1}^{n} a_p + \frac{1}{2}\bar{g}''(o)\sum_{p=1}^{n} a_p r_p^2 + \frac{1}{24}\bar{g}^{IV}(o)\sum_{p=1}^{n} a_p r_p^4 + \cdots. \tag{13}$$

By differentiating equation (12) we get

$$\bar{g}'(r) = r \cdot \bar{g}''(0) + \frac{1}{6} \cdot r^3 \cdot \bar{g}^{IV}(0) + \cdots . \tag{14}$$

Let us choose coefficients a_n such that $\sum_{p=1}^{n} a_p = 0$. Combining (11), (13), and (14) we get

$$kr\bar{g}''(0) + k\frac{r^3}{6}\bar{g}^{IV}(0) + \cdots = \frac{1}{2}\bar{g}''(0)\sum_{p=1}^{n} a_p r_p^2 + \frac{1}{24}\bar{g}^{IV}(0)\sum_{p=1}^{n} a_p r_p^4 + \cdots . \tag{15}$$

We now solve equation (15) for r and k in terms of the a_p's and r_p's. Starting with

$$\left.\begin{aligned} kr &= \frac{1}{2}\sum_{p=1}^{n} a_p r_p^2 \\ k\frac{r^3}{6} &= \frac{1}{24}\sum_{p=1}^{n} a_p r_p^4 \end{aligned}\right\} \tag{16}$$

we obtain

$$r = \sqrt{\frac{\sum_{p=1}^{n} a_p r_p^4}{2\sum_{p=1}^{n} a_p r_p^2}} \tag{17}$$

and

$$k = \sqrt{\frac{\left(\sum_{p=1}^{n} a_p r_p^2\right)^3}{2\sum_{p=1}^{n} a_p r_p^4}} . \tag{18}$$

Equations (17) and (18) give the proper values for k and r. When k and r, as given in these equations, are used, the first five terms of a Fourier series are identical for equations (10) and (11). The number of terms to be included depends on the requirements for the accuracy of $R(g)$. Practical experience shows that, within the accuracy obtainable, it is convenient to include five terms of the series.

RELATION OF DEPTH TO RESIDUAL ANOMALY FOR A BURIED SPHERICAL MASS

Returning to equation (11), it is now desirable to investigate the first derivative of $g(r)$ a little further. For a subterranean mass m (Figure 1) we presume that the distance from the surface to the center of gravity is z. The horizontal

distance at the surface to the point of observation A is designated as R. Taking once again the average anomaly along a circle with center at A and radius r we have

$$\bar{g}(r, z, R) = \frac{\gamma m}{2\pi} \int_0^{2\pi} \frac{z \cdot d\phi}{(\sqrt{z^2 + R^2 + r^2 + 2Rr \cos \phi})^3}, \tag{19}$$

where ϕ is the angle between the respective radii r and R.

The derivative $\bar{g}'(r) = \partial \bar{g}(r, z, R)/\partial r$ is very simple to evaluate for the case $R = 0$, where we get

$$\psi(r, z, 0) = -\frac{\partial \bar{g}(r, z, 0)}{\partial r} = \frac{3\gamma m z r}{(\sqrt{z^2 + r^2})^5} \cdot \tag{20}$$

$\psi(r, , 0)$ has a maximum at $2r = z$, since

$$\frac{\partial \psi(r, z, 0)}{\partial r} = 3\gamma m z \cdot \frac{z^2 - 4r^2}{(\sqrt{z^2 + r^2})^7} \cdot \tag{21}$$

That is to say that the derivative computed from measurements along a circle of radius r will accentuate the effect of any spherical mass at a depth $z = 2r$. By varying r and obtaining the locations at which ψ has maxima or minima, we are able to fix the depth z to the center of gravity of the mass m. We must here stress that this is valid only for a single mass-point (or a homogeneous sphere), omitting any mention of how it works if other masses are exerting an influence at the same time.

APPLICATION TO GRIFFIN'S AND PETERS' METHODS

We will now proceed to examine some of the previous methods for determination of the residual gravity effects. The theory stated by Griffin (1949) is based upon the use of the average value of the gravity anomalies along a circle or in practice by approximation to a polygon. That means that the residual anomalies are given as the following expression

$$R(g) = g(0) - \frac{1}{n} [g_1(\rho) + g_2(\rho) + \cdots + g_n(\rho)] \tag{3}$$

where $g(0)$ is the anomaly in the center and ρ is the distance to the corners of the polygon (or the radius of the circle). Substituting in equation (17) we have to put

$$a_0 = 1; \quad a_1 = -1; \quad a_2 = a_3 = \cdots = a_n = 0; \quad r_0 = 0; \quad \text{and} \quad r_1 = \rho.$$

Hence we get $r = (1/\sqrt{2})\rho$ and using the relation $z = 2r$ we obtain a depth of $z = \sqrt{2} \cdot \rho$ for a mass-point or a spherical mass. This depth is the depth at which the mass-anomalies are emphasized particularly. Griffin says:

"It is therefore seen that the amount of residuals one obtains at a given point varies greatly with the *size* of the unit figure used. . . . The kind of figure used, then, is only of secondary importance relative to the *size* of figure used."

It will be seen from the examples given by Griffin that the residual anomalies are changing perceptibly when the radius is altered, and we know now that the variation of the radius ρ brings sources into focus at a depth, z, that varies with ρ as $z=\sqrt{2}\cdot\rho$. Further, the kind of figure used is without influence as far as the depth is concerned. When Griffin gets slightly different residual anomalies for different kind of figures, this is due to errors originating in observational uncertainties. We want to stress again that this method includes the full error in $g(0)$—the gravity value at the center.

Another theory has been developed by Peters (1949) making use of the second and fourth vertical derivatives of the anomalies. Peters has applied this form for the residual anomaly to magnetic data but the method can be applied to any other potential (such as gravitational) data as well. The following identities are given:

$$\frac{\partial^2 g}{\partial z^2} = 1.156\,\bar{g}(0) + 0.256\,\bar{g}(1) - 0.445\,\bar{g}(\sqrt{2}) - 1.359\,\bar{g}(\sqrt{5}) + 0.392\,\bar{g}(\sqrt{9.23}) \tag{22}$$

and

$$\frac{\partial^4 g}{\partial z^4} = 1.753\,\bar{g}(0) + 0.170\,\bar{g}(1) - 1.036\,\bar{g}(\sqrt{2}) - 2.384\,\bar{g}(\sqrt{5}) + 1.497\,\bar{g}(\sqrt{9.23}). \tag{23}$$

Here $\bar{g}(\rho)$ is the average value of the gravity anomalies $g(\rho, \theta)$ along a circle with the radius ρ and the center point $(x, y, 0)$ at the surface.

Referring to equation (17) we have the following numbers for substitution in equation (22):

$$a_0 = 1.156,\quad a_1 = 0.256,\quad a_2 = -0.445,\quad a_3 = -1.359,\quad \text{and}\quad a_4 = 0.392;$$
$$r_0 = 0,\quad r_1 = \rho,\quad r_2 = \rho\sqrt{2},\quad r_3 = \rho\sqrt{5},\quad \text{and}\quad r_4 = \rho\sqrt{9.23},$$

and we get $r=0.525\rho$. Then, using the relation (for a point source) $z=2r$, we finally get $z=1.05\rho$. It is usual to take the grid spacing as the distance ρ in either case. Since the grid spacing is normally one mile we see that $z=1.05\rho$ represents a depth of approximately one mile and $z=\rho\sqrt{2}$ corresponds to a depth of about 1.4 miles. With regard to the fourth vertical derivative of g we have to substitute the following numbers in Equation (23):

$$a_0 = 1.753,\quad a_1 = 0.170,\quad a_2 = -1.036,\quad a_3 = -2.384,\quad \text{and}\quad a_4 = 1.497;$$
$$r_0 = 0,\quad r_1 = \rho,\quad r_2 = \rho\sqrt{2},\quad r_3 = \rho\sqrt{5},\quad \text{and}\quad r_4 = \rho\sqrt{9.23}.$$

Hence equation (17) will give

$$r = \rho\sqrt{\frac{127,920}{-0.005}}.$$

It must be stressed that the two methods are not to be compared in the instance where r is imaginary or when too many terms have been included in the series. An imaginary r seems to indicate that the depth-gradient is a reality; however, it is no longer possible to define the depths which have been emphasized. On the other hand, if we increase a_4 by one thousandth from 1.497 to 1.498, or r_4^2 by one-hundredth from 9.23 to 9.24 the ratio under the square root will become positive. In either case the value of r will be a rather large number, which is to say that the fourth vertical derivative of g is throwing very deep-seated masses into relief. It is therefore interesting to note that Peters writes:

"In some instances, where used judiciously, the fourth derivative is also valuable."

and

"Fourth derivatives tend to oscillate rather widely unless excellent data are available and they should be used with considerable discretion."

DEPTH ESTIMATION FOR BURIED SPHERICAL MASS NOT UNDER POINT OF COMPUTATION

In practice it is possible to determine

$$\psi(r, z, R) = -\frac{\partial \bar{g}(r, z, R)}{\partial r}$$

by dividing the difference of the average values of the gravity anomalies ($\bar{g}(r_1)$ and $\bar{g}(r_2)$) by the difference between their radii ($r_1 - r_2$) or

$$-\frac{\bar{g}(r_1) - \bar{g}(r_2)}{r_1 - r_2}.$$

Equation (19) can be written in the form

$$\bar{g}(r, z, R) = \frac{\gamma m}{2\pi} \int_0^{2\pi} \frac{z d\phi}{[\sqrt{(z^2 + (r + R)^2 - 4R \sin^2 \phi)}]^3} \tag{19a}$$

or

$$\bar{g}(r, z, R) = \frac{\gamma m}{\pi [z^2 + (r + R)^2]^{3/2}} \int_0^{\pi} \frac{z d\phi}{(1 - \sin^2 \alpha \sin^2 \phi)^{3/2}} \tag{19b}$$

using the substitution

$$\alpha = \arcsin \sqrt{\frac{4Rr}{z^2 + (r + R)^2}}. \tag{24}$$

We define

$$\rho = \sqrt{z^2 + R^2 + r^2}. \tag{25}$$

Inserting this in (19b) and integrating, we get

$$\bar{g}(r, z, R) = \frac{2\gamma mz}{\pi(\rho^2 - 2Rr)^{3/2}} \sqrt{\frac{\rho^2 - 2Rr}{\rho^2 + 2Rr}}\, E(\alpha, 90), \tag{26}$$

where $E(\alpha, 90)$ is the Legendre's form for an elliptic integral of second class,

$$E(\alpha, \phi) = \int_0^{\phi} \sqrt{1 - \sin^2 \alpha \sin^2 \phi}\, d\phi.$$

By replacing (24) in (26) the equation becomes

$$\bar{g}(r, z, R) = \frac{2\gamma mz \cos \alpha}{\pi(\rho^2 - 2Rr)^{3/2}} E(\alpha, 90). \tag{27}$$

We proceed to determine

$$\psi(r, z, R) = -\frac{\partial \bar{g}(r, z, R)}{\partial r}$$

by help of (27) and get

$$\psi(r, z, R) = \frac{\gamma zm \cos \alpha}{\pi(\rho^2 - 2Rr)^{5/2}} \left[\frac{\rho^2 - 2r^2}{r} \cdot \sin^2 \alpha\, E(\alpha, 90) + \frac{\rho^2 - 2r^2}{r} \cos^2 \alpha [F(\alpha, 90) - E(\alpha, 90)] + 6(r - R)E(\alpha, 90) \right]. \tag{28}$$

Equation (28) has been evaluated by use of the derivatives

$$\frac{\partial E(\alpha, 90)}{\partial \alpha} = -\cot \alpha [F(\alpha, 90) - E(\alpha, 90)] \tag{28a}$$

and

$$\frac{\partial \alpha}{\partial r} = \frac{1}{2} \sin \alpha \cos \alpha \frac{\rho^2 - 2r^2}{r(\rho^2 - 2Rr)}. \tag{28b}$$

$E(\alpha, 90)$ is, as mentioned above, Legendre's form for an elliptic integral of the second class, and $F(\alpha, 90)$ is Legendre's form for an elliptic integral of the first class,

$$F(\alpha, \phi) = \int_0^{\phi} \frac{d\phi}{\sqrt{1 - \sin^2 \alpha \sin^2 \phi}}.$$

If we make use of the quantities defined in Figure 1, equation (28) takes the form

$$\psi(r, z, R) = \frac{\gamma z m}{\pi[(z^2 + (R - r)^2]^{3/2}(z^2 + (R + r)^2)^{1/2}}\left[\frac{4R(z^2 + R^2 - r^2)}{z^2 + (R + r)^2}\right.$$
$$\cdot E\left(\arcsin\sqrt{\frac{4Rr}{z^2 + (R + r)^2}},\ 90\right) + \frac{(z^2 + R^2 - r^2)[z^2 + (R - r)]^2}{r(z^2 + (R + r)^2)}$$
$$\cdot\left[F\left(\arcsin\sqrt{\frac{4Rr}{z^2 + (R + r)^2}},\ 90\right)\right.$$
$$\left. - E\left(\arcsin\sqrt{\frac{4Rr}{z^2 + (R + r)^2}},\ 90\right)\right]$$
$$\left. + 6(r - R)E\left(\arcsin\sqrt{\frac{4Rr}{z^2 + (R + r)^2}},\ 90\right)\right]. \tag{29}$$

It would have been possible to develop a similar solution if we had based the evaluation upon equation (10). In this case, we would have obtained a less

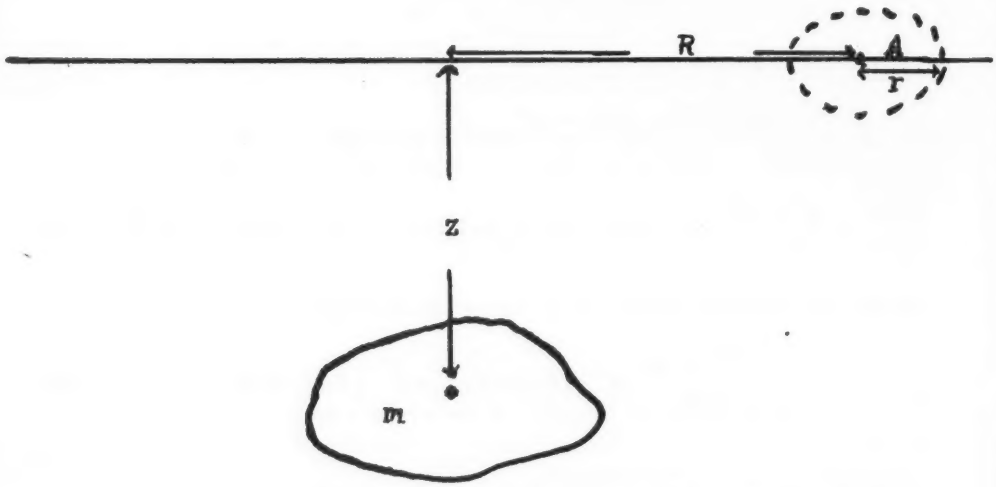

FIG. 1. A subterranean mass m has its center of gravity at the depth z from the surface. The point of observation A has a horizontal distance R from the vertical to the mass m. The radius of the small circle is r.

distinct picture since the series in equation (10) may converge quite slowly and if a_0 is not negligible the small local irregularities in gravity may be unduly reflected in the value of $\bar{g}(r_0)$. By using the method which resulted in equation (29), these small local irregularities are essentially eliminated. Neither equation (28) nor equation (29) is suitable for practical applications and in order to obtain a more useful expression we substitute again, this time replacing

$$\left.\begin{aligned} \frac{R}{z} &= p \\ \frac{r}{z} &= q \end{aligned}\right\}. \tag{30}$$

Consequently, we get

$$\left.\begin{aligned} \cos^2 \alpha &= \frac{1 + (p - q)^2}{1 + (p + q)^2} \\ \sin^2 \alpha &= \frac{4pq}{1 + (p + q)^2} \end{aligned}\right\}. \tag{31}$$

Inserting these quantities in (29), that equation becomes

$$\psi(r, z, R) = \frac{\gamma m \cos \alpha}{\pi z^3 (1 + (p - q)^2)^{5/2}} \left\{ \frac{1 + p^2 - q^2}{q} \sin^2 \alpha E(\alpha, 90) + \frac{1 + p^2 - q^2}{q} [F(\alpha, 90) - E(\alpha, 90)] + 6(q - p) E(\alpha, 90) \right\}. \tag{32}$$

This form for $\psi(r, z, R) = -\partial \bar{g}(r, z, R)/\partial r$ can be computed as a function of p and q by using tabulated values for Legendre's elliptic integrals (Emde, 1931). In Table I are given the values of $\psi(r, z, R)$ for various values of p and q. The corresponding curves have been plotted in Figure 2.

TABLE I

$c\psi$ AS A FUNCTION OF $p = \frac{R}{z}$ AND $q = \frac{r}{z}$;

(c IS A CONSTANT EQUAL TO $\frac{z^2}{\gamma m}$)

p \ q	0.1	0.2	0.5	1.0	2.0
0.0	0.292	0.544	0.859	0.530	0.107
0.1	0.270	0.522	0.824	0.528	0.107
0.2	0.247	0.460	0.773	0.522	0.108
0.5	0.075	0.167	0.417	0.466	0.116
1.0	−0.014	−0.021	−0.022	0.165	0.148
2.0	−0.004	−0.079	−0.028	−0.061	0.041
5.0	0.000	−0.004	−0.005	−0.002	−0.009
10.0	0.000	0.000	0.000	0.000	0.000

Analyzing Table I it is evident that ψ, as mentioned previously, is greatest in value when the center of the attracting mass is at a depth z such that $q = r/z = 0.5$. In other words, making use of a certain radius r, we get most of our gravitational

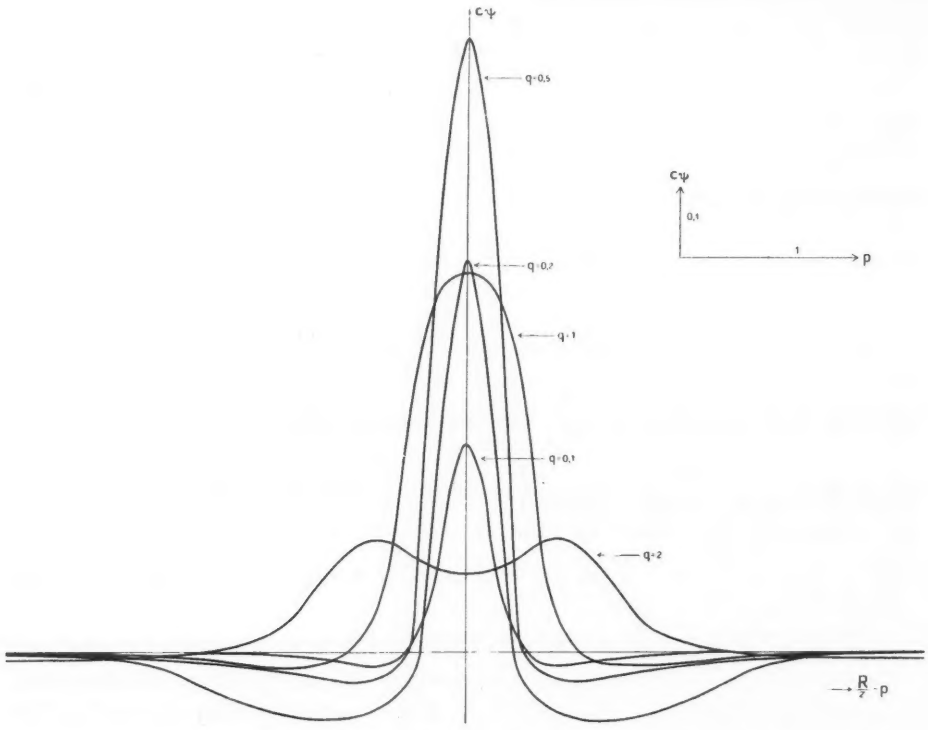

FIG. 2. $\psi(r, z, R) = -\dfrac{\partial \bar{g}(r, z, R)}{\partial r}$ as tabulated in Table I with respect to $p = \dfrac{R}{z}$ and $q = \dfrac{r}{z}$.

It is evident that the function has its sharpest peak at the depth $z = 2r$ when $q = 0.5$.

effect from mass anomalies at the depth $z = 2r$. Contributions from layers at other depths are attenuated and from Table I and Figure 2 it is seen how sharp this attenuation will be.

APPLICATION TO VERTICAL FAULT

We now proceed to consider the gravity effect of a vertical fault (Figure 3) and we will approximate the faulted layer by a horizontal sheet. If z is the mean depth to the slab, t its thickness and σ its density contrast it is possible to express the vertical gravity anomaly (Nettleton, 1940 and 1942) as follows

$$g\left(\frac{x}{z}\right) = 2\gamma\sigma t\left(\frac{1}{2} + \frac{1}{\pi}\ \text{arc tan}\ \frac{x}{z}\right). \tag{33}$$

Proceeding in the usual way, we obtain for the average gravity value along the circle with radius r

$$\bar{g}\left(\frac{x}{z},\ r\right) = \frac{\gamma\sigma t}{\pi}\int_0^{2\pi}\left[\frac{1}{2} + \frac{1}{\pi}\ \text{arc tan}\left(\frac{x + r\cos\phi}{z}\right)\right]d\phi. \tag{34}$$

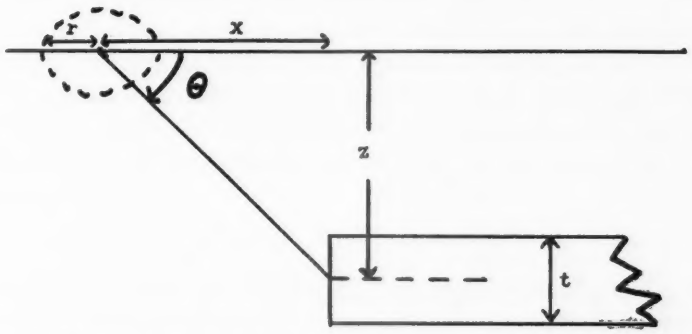

FIG. 3. Vertical fault. The faulted layer is approximated by a horizontal sheet of thickness t and mean depth z. The point at which the anomaly is calculated is a distance x from the fault and the angle the radius to the fault makes with the horizontal is θ. The radius of the small circle on the surface is r.

Once again we differentiate $\bar{g}$ with respect to r in order to get

$$\psi\left(\frac{x}{z},\ r\right) = -\frac{\partial \bar{g}\left(\frac{x}{z},\ r\right)}{\partial r}$$

$$\psi\left(\frac{x}{z},\ r\right) = \frac{\gamma\sigma t z}{\pi^2}\int_0^{2\pi} \frac{\cos\phi d\phi}{z^2 + x^2 + r^2\cos^2\phi + 2xr\cos\phi}. \tag{35}$$

By substituting $u = \tan\phi/2$, (35) will be altered to

$$\psi\left(\frac{x}{z},\ r\right) = \frac{2\gamma\sigma t z}{\pi^2}\int_0^{\infty} \frac{(1-u^2)du}{(1+u^2)^2(x^2+z^2)+(1-u^2)r^2+(1+u^2)(1-u^2)2xr} \tag{36}$$

and the integral can be reduced to the sum of a set of simpler fractions. However, the fractions are very complicated and the integration and further development of the function are very laborious. The function can be reduced to the form:

$$\psi\left(\frac{x}{z},\ r\right) = -\frac{\gamma\sigma t z^2}{\alpha^2 - \beta^2}\left[\frac{1+\alpha^2}{\alpha} - \frac{1+\beta^2}{\beta}\right] \tag{37}$$

where α and β are determined by

$$\left.\begin{aligned} \alpha^2 + \beta^2 &= 2(x^2 + z^2 - r^2) \\ \alpha^2\beta^2 &= z^2 + x^2 + r^2 + 2xr \end{aligned}\right\}. \tag{37a}$$

We have, therefore, preferred to calculate the function $\psi(x/z,\ r)$ by numerical integration and we have plotted the results in Figure 4.

It will be seen from Figure 4 that it is not possible in the case of the vertical fault to define the depth from which ψ has its greatest contribution and we con-

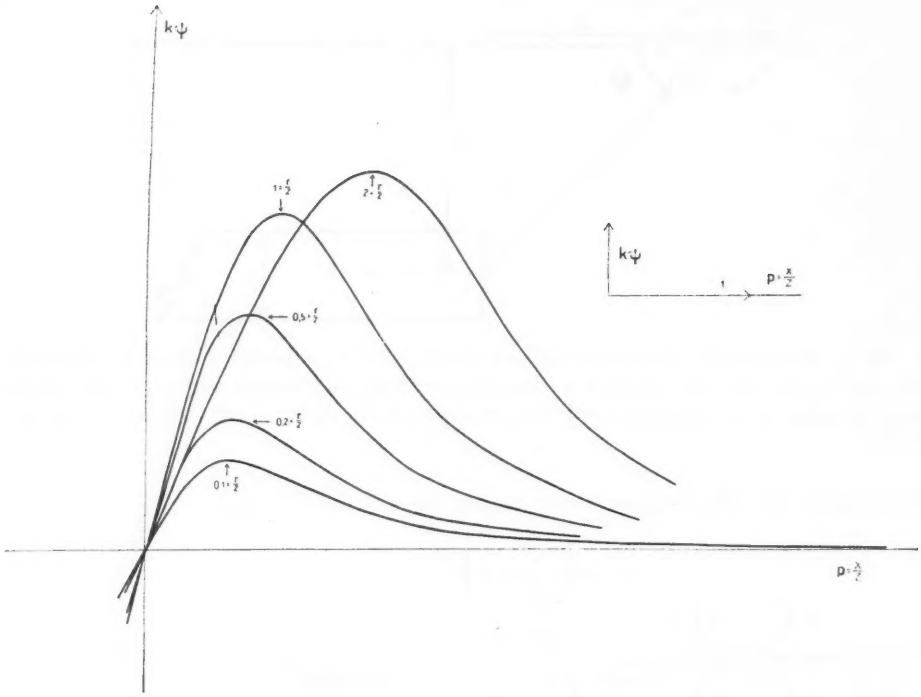

FIG. 4. The function $\psi\left(\frac{x}{z}, r\right) = -\frac{\partial \bar{g}\left(\frac{x}{z}, r\right)}{\partial r}$ for a vertical fault computed by numerical integration from equations (37) and (37a). The ordinate is $k\psi$, where k is a constant containing t and σ.

clude that this procedure is not applicable for depth estimation as far as the vertical fault is concerned.

SUMMARY

In practice, our procedure for determining the residual anomaly, as we define it, is the following:

The point under consideration is taken as the center point for two circles, the radii being r_1 and r_2. We have then to set up the difference

$$\frac{1}{r_2 - r_1}\left[\frac{1}{n}\left\{g_1(r_1) + g_2(r_1) + \cdots + g_n(r_1)\right\} - \frac{1}{m}\left\{g_1(r_2) + g_2(r_2) + \cdots + g_m(r_2)\right\}\right].$$

It is convenient to use a template designed for two concentric circles and with the help of a calculating machine it is an easy task to average the figures obtained from the readings of the template. An experienced interpreter is able to pick the right radii upon his first, or at least his second, try.

By using this method, any subterranean anomalous mass of approximately spherical form at a depth $z=2r=r_1+r_2$ is thrown into relief and at the same time the effect of masses at greater or lesser depth is almost eliminated. The method is not, however, suitable for the vertical fault. In particular, we want to emphasize that the term "residual anomaly" as it is used in most cases can be expressed by the equation

$$R(g) \equiv a_0\bar{g}(r_0) + a_1\bar{g}(r_1) + \cdots = k\bar{g}(r).$$

Included in this definition are the average anomaly method along a circle or a polygon and the methods using the second and the fourth derivatives of g.

We have formulated the following quantities:

$$r = \sqrt{\frac{\sum_{p=1}^{n} a_p r_p^4}{2\sum_{p=1}^{n} a_p r_p^2}}$$

and

$$k = \sqrt{\frac{\left\{\sum_{p=1}^{n} a_p r_p^2\right\}^3}{2\sum_{p=1}^{n} a_p r_p^4}}.$$

Furthermore we have developed a convenient procedure for applying the identity

$$\psi(r, z, R) = -\frac{\partial\bar{g}(r, z, R)}{\partial r} = -\frac{\bar{g}(r_1) - \bar{g}(r_2)}{r_1 - r_2},$$

where $r=\frac{1}{2}(r_1+r_2)$, to observed gravity data.

As far as the second and fourth derivatives of g are concerned, we should like to state that these figures do not represent a depth gradient but a residual anomaly. We quote from Peters (1949):

"These methods, being approximations, give results which depend to a considerable extent on the spacing used."

The formulas used in order to work out suitable expressions for the second and fourth vertical derivatives of g do not seem to be convergent. Nevertheless, the second vertical derivative method seems to be well fitted for practical applications and the method emphasises the effect of subterranean masses at the depth $z=1.05\rho$, where ρ is a function of the grid spacing.

The method which has been described in this paper for the determination of residual anomalies is independent of the grid spacing. Further, the random errors due to the observational data do not have the same influence upon the residual anomalies that they do when these anomalies are computed by the average circle and average polygon methods.

Finally, our procedure specifies the depth to the subterranean masses which give rise to minima or maxima in the first derivatives of average gravity, in terms of the radial distance at which the turning points occur. As far as the vertical fault is concerned, the residual anomalies do define the fault; it is not possible, however, to define the depth by this means. The problem of determining the depth to a vertically faulted bed is under consideration and we are planning another paper on this subject.

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THE MICROLOG CONTINUOUS DIPMETER*

PIERRE DE CHAMBRIER†

ABSTRACT

Some of the methods used at the present time for determining the angle and the azimuth of the dip in the formations traversed by a borehole are based on correlations between three curves recording certain electrical characteristics of the formations, such as *SP* or resistivity, along the wall of the borehole in three equally spaced azimuths. With the conventional equipment used for the application of these methods, the measurements are made over separate intervals of depth.

In the present paper, a new improved instrument called the MicroLog Continuous Dipmeter is described, wherein the three curves used for the determination of the dip are obtained with three MicroLog devices and wherein these three curves—as well as the orientation of the instrument and the inclination of the borehole—are simultaneously and continuously recorded.

It is shown that with the help of this instrument more numerous dip determinations can be made in a given well with a higher accuracy and a greater recording speed.

The paper is illustrated with field examples.

INTRODUCTION

An important factor in oil exploration is a knowledge of the dip of the formations, which makes possible the correct location of offset and/or side-tracked wells after one well has been drilled in a given area and which, more generally, helps in the solution of stratigraphic and structural problems such as determination of unconformities or of faults and investigation of stratigraphic traps.

Inasmuch as the evaluation of the dip by correlation between several wells is complex, costly, and very often uncertain, efforts have been made to measure the angle and direction of the dip of the strata traversed by a single borehole. One method developed about twenty years ago was based on the electrical anisotropy of sedimentary formations and was carried out by means of appropriate electrical measurements (Schlumberger and Doll, 1933). This method was later abandoned and replaced by more convenient and accurate methods which are in standard use at the present time. These are based essentially upon the correlation between the *SP* (spontaneous potential) or the resistivity curves recorded along the wall of the borehole by means of three systems of properly oriented electrodes (Doll, 1943; Stratton and Hamilton, 1947).

With these methods, the process is essentially discontinuous and the angle and the direction of the dip are measured at separate intervals of about 20 ft to 40 ft which are selected from the electrical logs before running the instrument.

Another method has been recently introduced which operates continuously. In this a comparison is made between the caliper profiles of the wall of the borehole in three oriented planes containing the axis of the hole (Boucher, Hildebrandt, and Hagen, 1950).

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The present paper relates to a new instrument with which the angle and direction of the dip can be continuously recorded. One essential feature of this system is that the curves used for the correlation are MicroLog curves (Doll, 1950) recorded along the wall of the hole. This system also gives, simultaneously, a continuous record of the angle and of the azimuth of the borehole drift.

The present paper contains a description of the essential features of the instrument and an outline of the field equipment. The results obtained with it are presented and explained and examples are given of its application.

ESSENTIAL FEATURES OF THE INSTRUMENT

The basic principles of the method using the present instrument are discussed by Doll (1943) and Stratton and Hamilton (1947). The following explanations will deal mainly with the novel features involved in the application of these principles to dip determination.

The electrical measurements are made along the wall of the borehole by means of MicroLog devices.

It is recalled that a MicroLog is a resistivity log recorded with electrodes (usually three) spaced at short distances from each other (about 1 in.–2 in.) in an insulating pad which is pressed against the wall of the drill hole. Under these conditions, the system measures the average resistivity of the small volume of material which is located behind the pad and which is therefore electrically shielded against the short-circuiting action of the mud.[1]

In the present instrument, the subsurface apparatus comprises three identical MicroLog devices, separated from each other by 120° in such a way that the centers of all three devices are in the same plane perpendicular to the axis of the apparatus. This axis practically coincides with the axis of the borehole, because the subsurface apparatus is long (16 ft over-all) and is kept centered by means of appropriate spring systems.

When the instrument is moved along the borehole, three curves are recorded simultaneously. These give respectively the resistivities of the formations at short distance from the wall and in three equally spaced azimuths (Fig. 1). At the moment the MicroLog devices cross the boundary between two formations with different resistivities, such as *A* or *B* on Figure 1, the corresponding shifts in the curves occur at different depths as a result of the dip of the formations. The geometric elements of the dip (direction and angle) can be derived from the values of these differences in depth. To this end, the orientation of the electrode systems should be known. Furthermore, as the borehole is generally not vertical, the direction and angle of the axis of the instrument (which coincides with the axis of the borehole) should be also determined. These data are obtained by means of an appropriate teleclinometer attached to the dipmeter system.

The continuous recording of the dipmeter curves throughout the borehole has the advantage of giving a great number of intervals where correlations can

[1] In order to simplify the drawing, the pads of the MicroLog systems are not represented in the schematic figures given with the present paper.

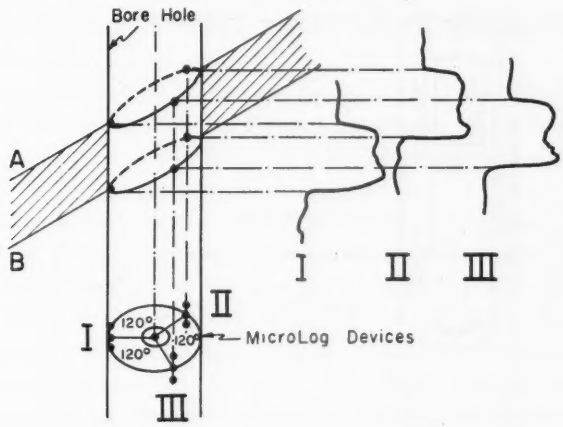


FIG. 1. Schematic drawings of dipmeter curves.

be made, and where the dip can accordingly be determined. This feature appreciably increases the amount and accuracy of the information to be obtained from a survey, while the time spent for the operation is comparatively small.

The use of MicroLog devices offers additional advantages. Because of the short electrode spacing used and the shielding action of the pad, the MicroLog makes possible a detailed record of many variations in formation resistivity which are not shown clearly or may even be missed with other devices. A greater number of zones or points is thus made available for correlation throughout a given depth interval. Also, the boundaries between the beds are more sharply defined by the MicroLog. This makes the correlations easier and more accurate.

Field Equipment

A schematic representation of the circuits used on the subsurface equipment is given in Figure 2. This figure shows, from the bottom to the top:

The dipmeter system, including the three MicroLog devices and the dipmeter transmitter.

The teleclinometer system, including:

a) the pendulums used for the measurement of the angle and azimuth of the drift of the borehole;

b) the magnetometers used for recording the azimuth of the one of the MicroLog devices taken as the reference and designated as Electrode I;

c) the compass and inclination transmitter; and

d) the power supply and the oscillators which are fed from the surface and which are designed to furnish the necessary current to the various elements of the teleclinometer.

Dipmeter

The dipmeter system, as already explained, essentially comprises three MicroLog devices applied to the wall of the hole by means of three appropriate

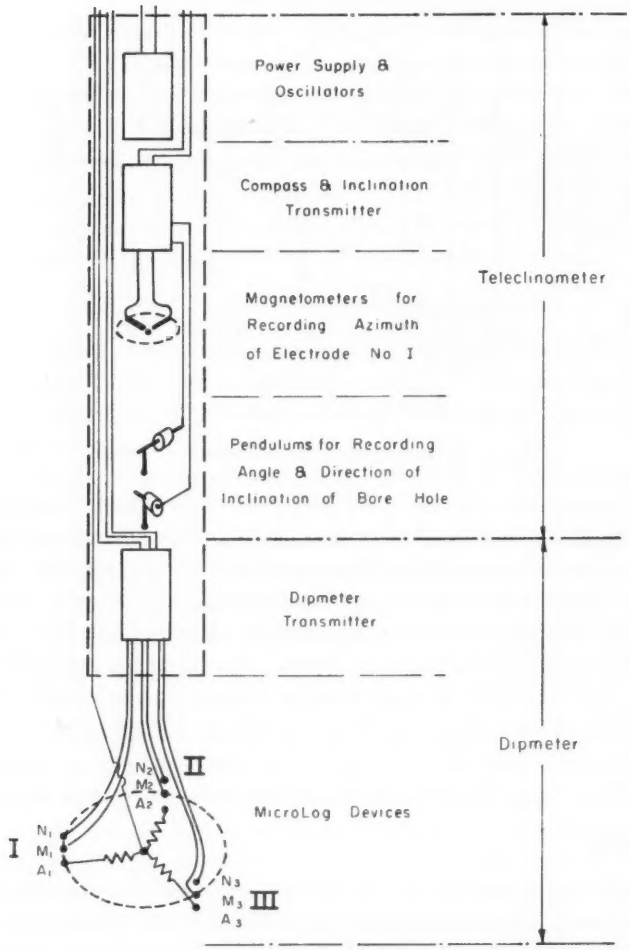


FIG. 2. MicroLog continuous dipmeter—schematic drawing of bottom hole circuits.

springs located 120° apart. An alternating current of constant intensity is sent from the surface and is divided into three equal parts which flow respectively through the three power electrodes A_1, A_2, and A_3 of the MicroLog devices. The corresponding potential differences between the respective pickup electrodes of the MicroLog devices (M_1N_1, M_2N_2, and M_3N_3) are applied to the input end of the dipmeter transmitter, where they are amplified, rectified, and sent to the surface.

Teleclinometer

The teleclinometer is designed to make possible the continuous recording at the surface of a) the azimuth of the reference electrode (I) which gives the ori-

entation of the instrument, and b) the angle of inclination (or drift) of the hole and the azimuth of the inclination.

a) Azimuth of Electrode I. In one of the earlier instruments, namely the photoclinometer, the orientation of the instrument at any given level is obtained by photographing a compass needle and a marker showing the azimuth of the reference electrode.

With the present instrument, the orientation is continuously recorded by means of a system of two or more magnetometers, which comprise essentially a core of high permeability alloy, such as permalloy, inserted within two coaxial coils. The saturation of the core is modified by the earth's magnetic field according to its orientation. Accordingly, if an alternating current of constant intensity is fed through the primary coil, the characteristics of the current induced in the secondary coil depend on the orientation of the magnetometer. In the present equipment, the intensity of one of the harmonics of the induced current is used to determine the orientation.

It is thus possible to measure the azimuth of Electrode I continuously by using, for example, two magnetometers, located at right angles to each other, which are kept in a horizontal plane by a gimbal suspension. The orientations of each magnetometer are fixed with respect to the azimuth of Electrode I. The signals received in the secondaries of the two coils are filtered in the compass and inclination transmitter and sent to the surface. The respective signals are the components of a vector which gives the azimuth of the instrument with respect to the magnetic north.

In the present equipment, the vectorial addition of the two (or more) components is made automatically by means of electromagnetic devices such as selsyns or resolvers.

b) Angle and Azimuth of the Inclination of the Borehole. Let us consider the "Inclination Vector," i.e. the projection on a horizontal plane of a vector of unit length parallel to the axis of the borehole. The amplitude of the inclination vector is proportional to the sine of the angle of drift of the hole and, accordingly, gives a measure of this angle; the azimuth of the inclination vector with respect to the magnetic north is the azimuth of the drift.

With the photoclinometer, the inclination vector is determined by taking a picture of a compass needle together with a ball rolling on a curved glass. This process provides for a determination in polar coordinates.

With the present system, the components of the inclination vector along two rectangular coordinates are continuously recorded. To this end, two pendulums are used which can swing in two planes perpendicular to each other and whose axes of suspension are respectively perpendicular to the axis of the instrument. Accordingly, the angles of rotation of these pendulums with respect to their position when the borehole is vertical are proportional to the two components of the inclination vector.

For the transmission of the components, each suspension axis, which rotates

together with its pendulum, is made to actuate a device producing an electrical signal proportional to the angle of rotation. The device can be a potentiometer or a system of coils whose coupling changes with the rotation of the pendulum axis. The signals are sent to the surface through the compass and inclination transmitter.

The signals recorded at the surface are the components of a vector related to a coordinate system which is in a fixed position with respect to the instrument and which therefore rotates at random with the instrument. Inasmuch as the orientation of the instrument is known (from the azimuth of Electrode I) it is possible to relate the inclination vector to the magnetic north. This can be done automatically by means of an appropriate electromagnetic system at the surface which rotates the coordinates so that one coordinate axis is made to coincide with the North-South direction and the other axis with the East-West direction. Finally, with this automatic system the recorded curves give the components of the inclination vector in the North-South and East-West directions respectively.

Transmission of Signals

The signals to be transmitted to the surface are the following: three dipmeter signals, two or more magnetometer signals, and two inclination signals (one from each pendulum).

Actually, whereas the continuous transmission of the dipmeter signals is indispensable, there is no such necessity in the case of the azimuth and inclination signals, since their variation with depth is comparatively slow. It is sufficient to obtain indications of azimuth and inclination approximately every five seconds. Accordingly, the telemetering requirements for the teleclinometer are not as severe in principle as for the dipmeter.

In order to transmit simultaneously several signals with a limited number of conductors, a plurality of alternating currents may be used which cover a rather wide frequency spectrum—for example 0 to about 20,000 cycles per second. The spectrum is divided into several channels, each of which is used for one of the signals to be transmitted. This system is used with the instruments in the field at the present time.

All the circuits of the subsurface equipment have been designed to work with stability at the high temperatures which may prevail in deep wells (up to 400°F.).

With the recording apparatus used at the present time, the maximum logging speed is 3,000 ft per hour, and it can be expected that this speed will be increased in the future when faster recorders are introduced.

The minimum hole diameter that can be surveyed depends on the dipmeter electrodes: with the earlier type equipment the minimum diameter is 7″, with the more recent type it is $5\frac{1}{2}$″.

Figure 3 and Figure 4 are photographs respectively of the subsurface equipment and of the control panels used at the surface.

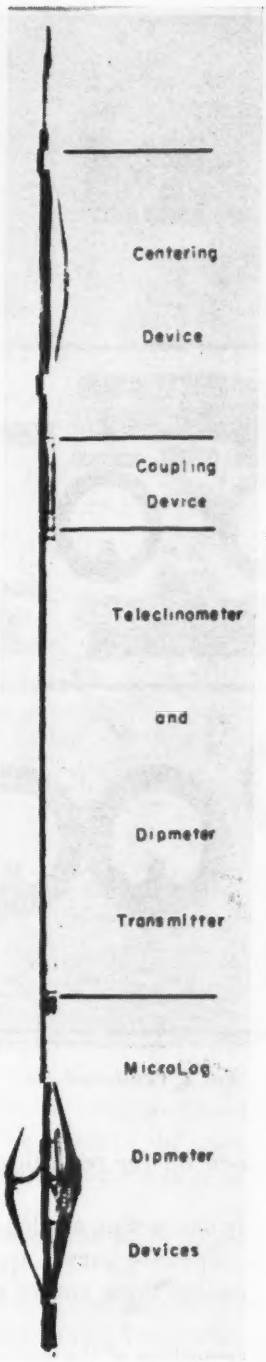


FIG. 3. Subsurface equipment.

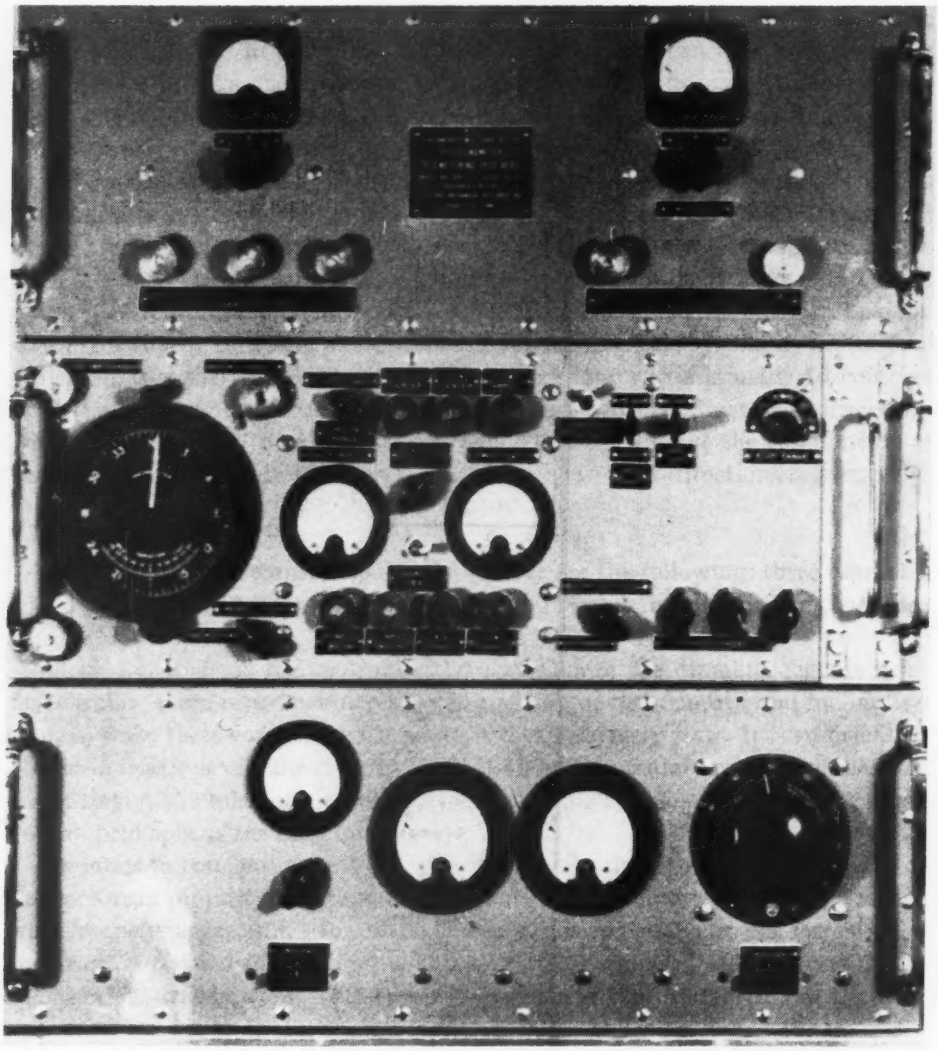


FIG. 4. Control panels.

Presentation of the Log

The depth scale actually used for the recording of the curves is 1/20, i.e. 6 inches for 10 feet.

Figure 5 shows schematically one section of a log extending over a depth interval of about ten ft. The three dipmeter curves are recorded on the right hand track. The left hand track contains three curves giving the indications of the teleclinometer.

The thin solid curve is the recording of the azimuth of the dipmeter reference electrode (Electrode I) from 0° to 360°, 0° being on the left side of the track. In the

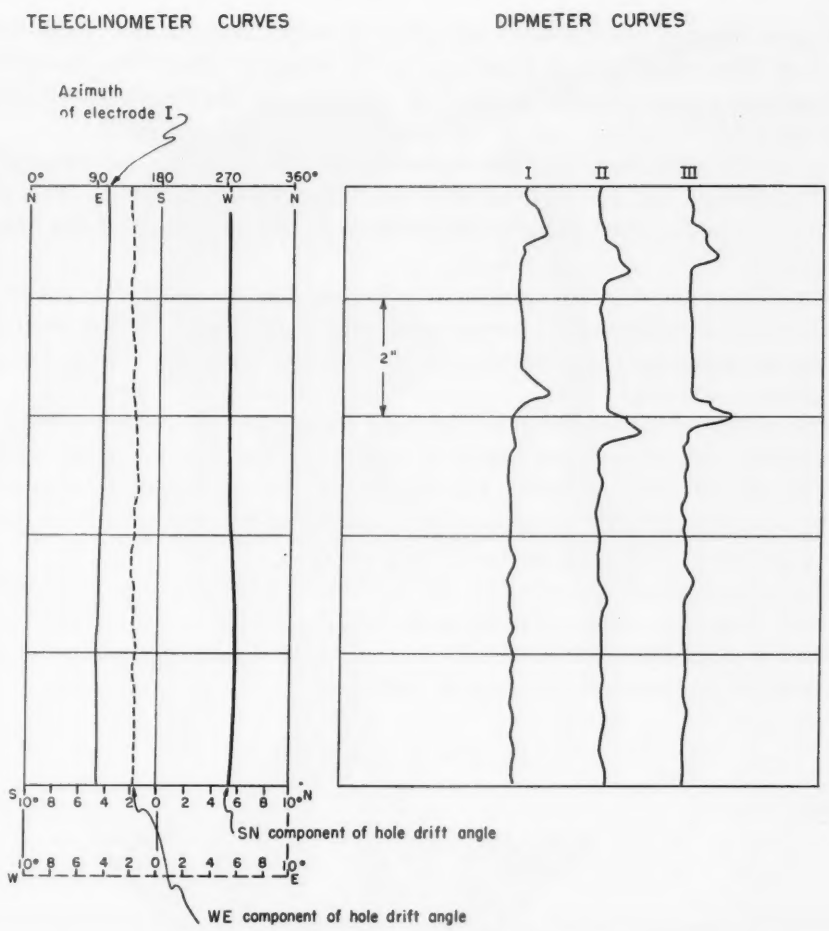


FIG. 5. Schematic example of log.

present example, which shows a very short section, this curve is almost a vertical straight line. For long recordings, the azimuth may vary considerably; when it reaches the value of 360° and over, the curve jumps back to the left of the track.

The heavy solid curve shows the component of the drift angle of the hole in a North-South vertical plane. The origin of the scale is at the center of the track, the north inclinations being recorded on the right side, and the south inclinations on the left side.

The third curve, dashed, shows the East-West component, east being on the right side and zero at the center.

The scale generally extends 10° from the center of the track. The teleclinometer is, nevertheless, capable of measuring the drift up to 90°, a much greater value than earlier instruments could measure.

To make use of the log, the two components of the drift are plotted along two

rectangular axes of coordinates, corresponding respectively to the North-South and East-West directions as illustrated in the example below. The direction of the resultant vector gives the azimuth of the drift and the length of this vector gives the angle of drift.[2]

As already explained, the drift azimuth and drift angle are not recorded in polar coordinates but are resolved into two rectangular components. This is an added convenience when plotting graphs showing the total drift of the bottom of the hole.

The displacement of the anomalous points on the three dipmeter curves are measured by superimposing a transparent print of the log on the log itself, and moving the print until the best correlations are found between curves I and II and curves I and III.

The measured values should be corrected for hole drift in order to obtain the angle of dip with respect to a horizontal plane and the azimuth of dip with respect to the direction of north. The translation is usually made by means of a special apparatus which reconstructs the geometry of the borehole. A picture of one such type of apparatus is shown in Figure 6.

It is also possible to make the same translation by graphical or analytical methods. It can be shown, for example, that the azimuth of dip, with respect to the azimuth of the electrode which corresponds to the curve where the anomalous point is the lowest, is given by the equation:

$$\tan \beta = \sqrt{3}\,\frac{\lambda - 1}{\lambda + 1},$$

where

$$\lambda = \frac{h_2}{h_1},$$

h_1 being the elevation difference between the lowest curve and the curve following it in the cyclic permutation I–II–III–I, and h_2 being the elevation of the remaining curve above the lowest one. Using the same notation, the apparent angle of dip α_a, i.e., the angle between the plane determined by the three anomalous points and a plane perpendicular to the axis of the hole, is given by:

$$\tan \alpha_a = \frac{2}{3}\,\frac{h_1}{r}\,\sqrt{\lambda^2 - \lambda + 1}$$

where r is the radius of the hole.

With the earlier type of apparatus, the value of r was taken as being equal to half the nominal bit size. In the new improved instrument a section gauge device is involved which will record the borehole diameter simultaneously with the dipmeter curves.

[2] This graphical construction is not rigorously accurate, but is sufficient in practice, since with the small angular values generally involved, the angles are substantially equal to their tangents.

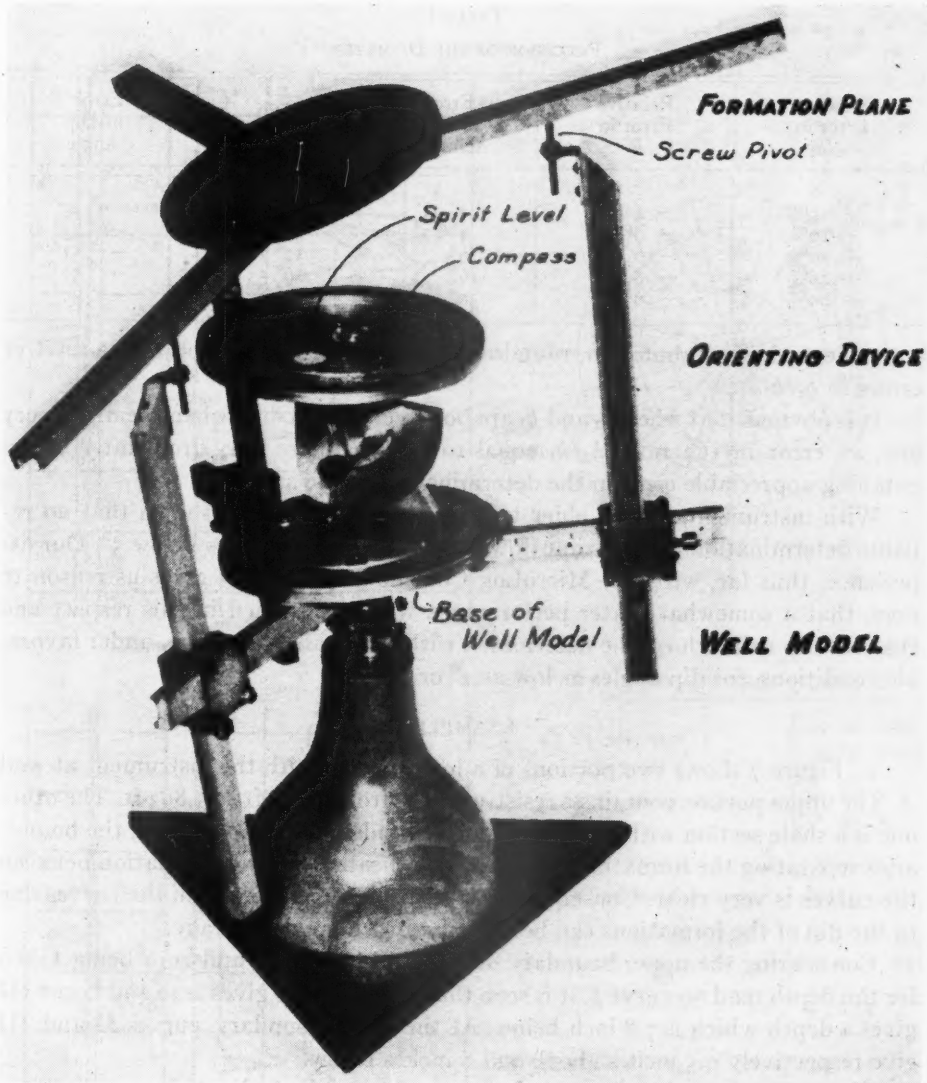


FIG. 6. Dipmeter interpretation apparatus.

Accuracy of the Instrument

Some hypothetical figures are given below to illustrate the accuracy of the instrument. It is supposed for simplicity that $h_2 = h_1$, and $h_1/r = 1/2$. In this case, the azimuth β of the dip referred to the azimuth of the electrode corresponding to the lowest curve is zero, and the apparent dip angle is 18° 25′.

Table I gives the values which would be obtained for β and α_a with various relative errors made in the values of h_1, with h_2 being supposed unchanged. For

TABLE I

PRECISION OF THE DIPMETER

Relative Error in h_2/h_1	Relative Error in h_1	Error in Dip Azimuth	Dip Angle	Error in Dip Angle
0		0	18° 25′	
+ 5%	− 4.8%	2° 25′	18° 00′	−0° 25′
+ 10%	− 9%	4° 40′	17° 40′	−0° 45′
+ 20%	−16.6%	9°	17° 14′	−1° 11′
+ 40%	−28.5%	16°	16° 33′	−1° 52′
+100%	−50%	30°	16° 05′	−2° 30′

convenience in the tabulation, round numbers have been ascribed to the relative errors in h_2/h_1.

It is obvious that when h_2 and h_1 are both very small, i.e., when the dip is very low, an error in the ratio h_2/h_1 equal to 40% or more may frequently occur, entailing appreciable error in the determination of the azimuth.

With instruments of the older types long experience had shown that no reliable determination of dip azimuth was possible for dip angles below 5°. Our experience, thus far, with the MicroLog Continuous Dipmeter gives us reason to hope that a somewhat better performance will be obtained in this respect and that the dip azimuth can be determined with reasonable accuracy, under favorable conditions, for dip angles as low as 2° or 3°.

EXAMPLES

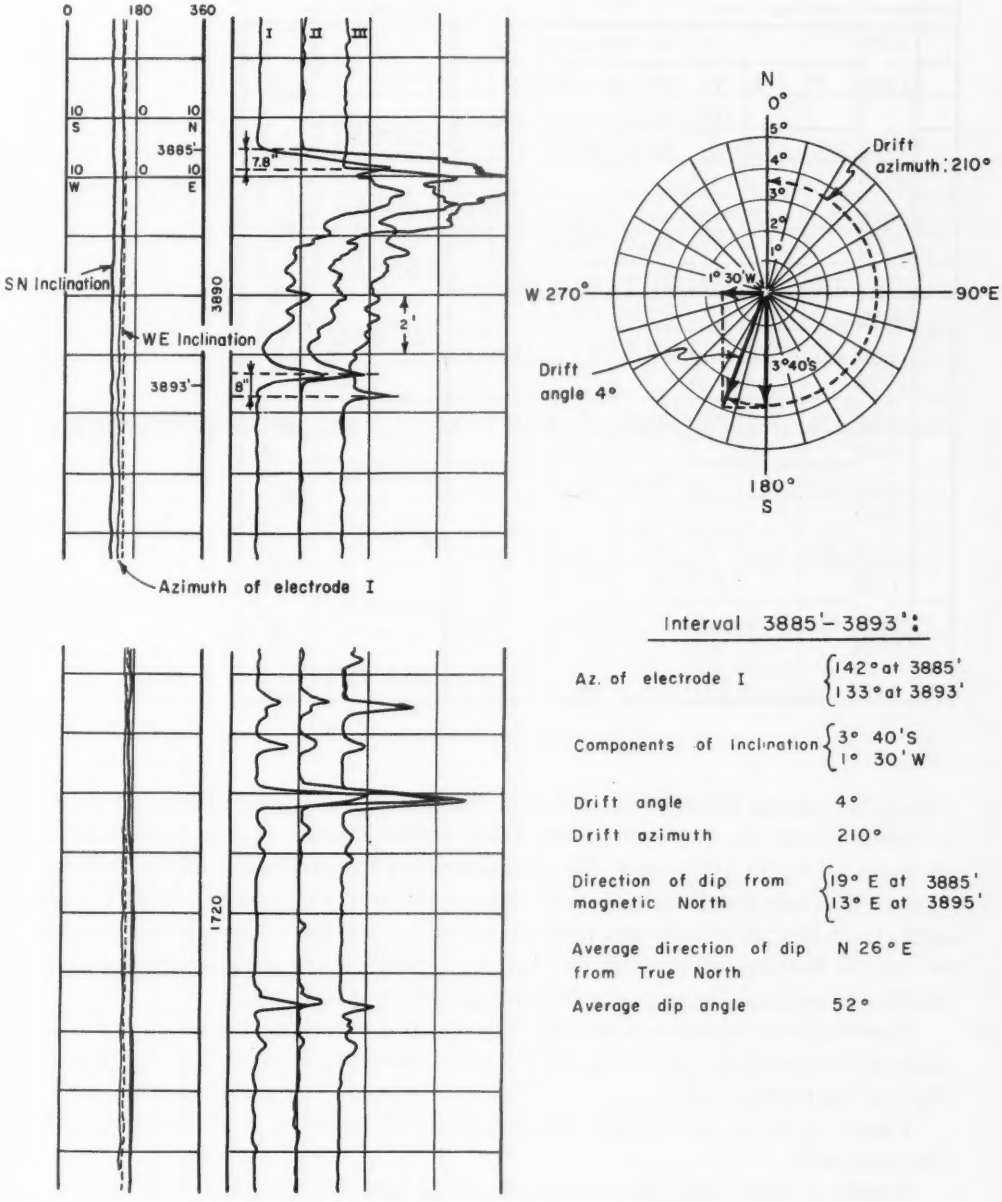
1. Figure 7 shows two portions of a log recorded with the instrument at well *A*. The upper portion contains a resistive sand, from 3,885 ft to 3,893 ft. The other one is a shale section with streaks of lime or sandstone. In both cases, the boundaries separating the formations are sharply indicated and the correlation between the curves is very clear. Consequently, the displacement between the curves due to the dip of the formations can be measured with great accuracy.

Considering the upper boundary of the sand (3,885 ft), and zero being taken for the depth read on curve I, it is seen that curve II also gives zero and curve III gives a depth which is 7.8 inch below. At the lower boundary, curves II and III give respectively 0.5 inches above and 8 inches below.

The values for azimuth of the reference electrode, inclination angle components, drift, and dip are all shown in the lower right hand portion of Figure 7.

A table of dip determinations for the same well is shown in Figure 8. This example shows an abrupt change in the geometric elements of the dip around the depth of 2,600 ft. Above this level, between about 2,100 ft and 2,560 ft the direction of dip is South-East, and the angle of dip varies between 17° and 27°; below 2,600 ft the direction of dip changes to North-East, and the angle of dip reaches 47°, with similar characteristics being observed down to 3,895 ft. This circumstance indicates the presence of an unconformity at about 2,600 ft.

2. Figures 9 and 10 show respectively two portions of the dipmeter and tele-



Interval 3885'–3893':

Az. of electrode I	142° at 3885' 133° at 3893'
Components of Inclination	3° 40'S 1° 30'W
Drift angle	4°
Drift azimuth	210°
Direction of dip from magnetic North	19° E at 3885' 13° E at 3895'
Average direction of dip from True North	N 26° E
Average dip angle	52°

FIG. 7. Actual example of log (Well A—Oklahoma).

STATION	Depth Interval	Drift Azimuth	Drift Angle	Orient No. 1	Displacement of curves in reference to I II	III	Direction	Dip	AVERAGE DIRECTION	AV DIP	Graph of Direction
	1200 to 1222	0	0	0	No consistent Dip or trend						
	to 1518	225	1.2	330 95	D4.2 U1.6	D3.0 U4.1	134 132	32 36	S-37-E	34	
	2070 to 2090	243	2.2	94 93	0	U2.2	148	17	S-22-E	17	
	2164 to 2190	238	2.6	197 210	U1.6 U1.7	D0.1 D0.6	123 126	14 17	S-46-E	15	
	2434 to 2438	248	3.2	25	U1.6	0	132	15	S-38-E	15	
	2550 to 2560	254	3.3	63	D2.7	U1.2	158	27	S-12-E	27	
	2620 to 2626	243	3.2	92	U8.0	U3.4	57	47	N-67-E	47	
	2660 to 2668	255	3.2	67	U6.3	U6.1	64	43	N-74-E	43	
	3390 to 3400	248	2.7	350 315	0 D1.0	U4.3 U4.3	49 28	34 37	N-48-E	35	
	3885 to 3895	210	4.0	142 133	0 U0.5	D7.8 D8.0	19 13	52 53	N-26-E	52	

UNCONFORMITY

FIG. 8. Table of dip determination (Well A).

clinometer curves recorded in well B in Oklahoma. Correlation lines are traced in dashes across the dipmeter curves. Each portion extends over a depth interval of about 30 ft. In both cases, the components of the inclination of the hole are very small (hole practically vertical). Along the interval shown in Figure 9 the azimuth of Electrode I changes from about 180° at the top of the section to about 60° at the bottom, whereas in the case of Figure 10, the instrument has practically not rotated, the azimuth remaining equal to about 110°.

Figure 9 is an example of low dip (6°), which is determined with accuracy because of the excellent correlation between the curves. In Figure 10, a case of large dip (51°) is represented.

Figure 11 shows an example of comparatively large dip (25°) determined in the same well.

Figure 12 shows the conventional electrical logs (*SP* and resistivity) and the results of dip measurements along a larger section of the same well. The depth scale is much smaller for these logs. Thanks to the continuous recording of the dipmeter and teleclinometer signals along the borehole, a great number of dip determinations have been made. This makes possible a good check on the con-

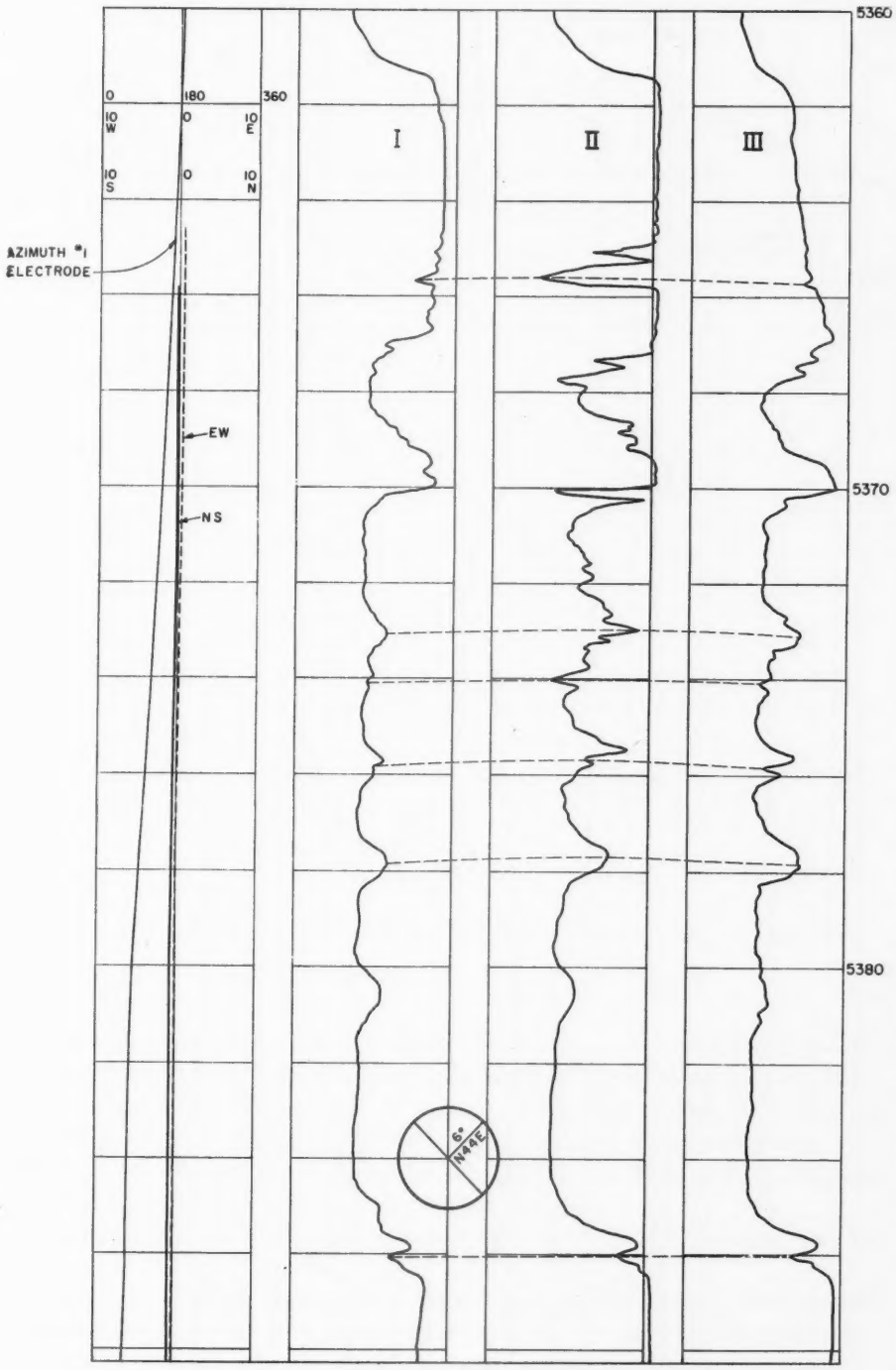


FIG. 9. Example of determination of low dip (6°). (Well B—Oklahoma).

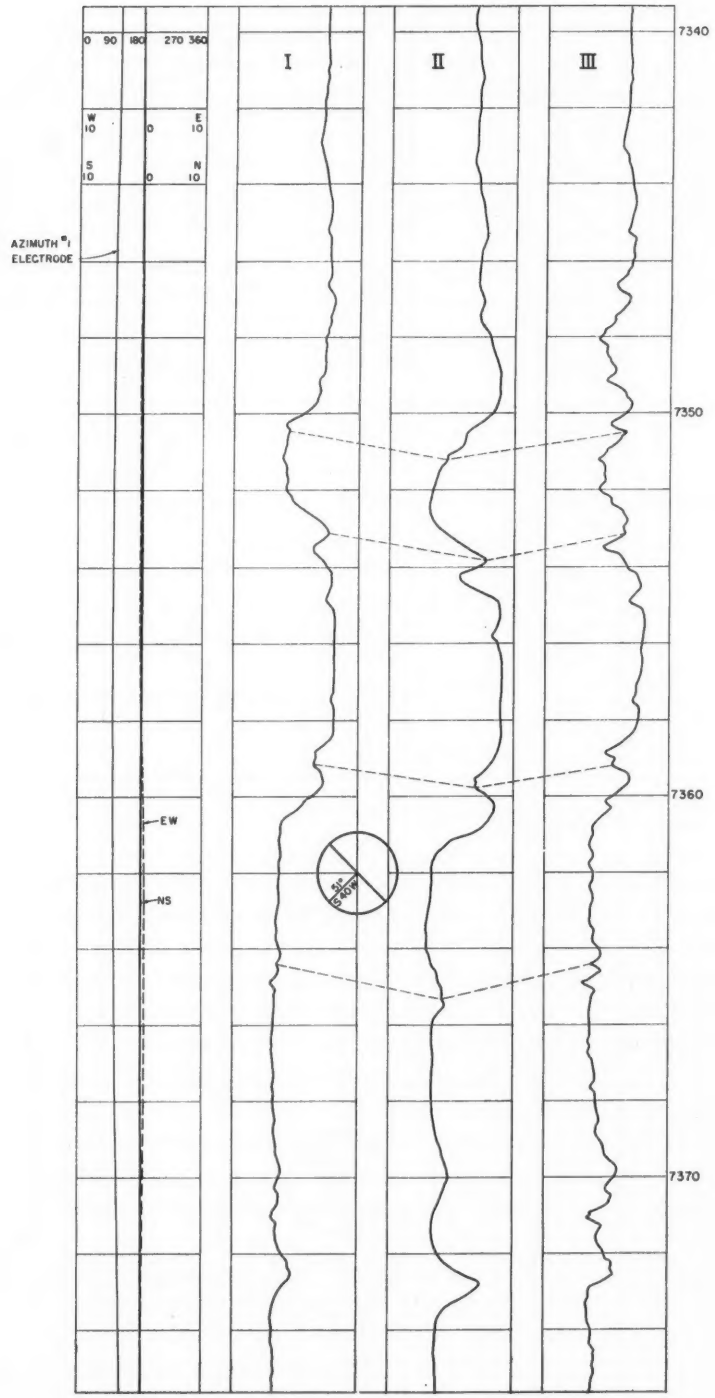


FIG. 10. Example of determination of high dip (51°). (Well B).

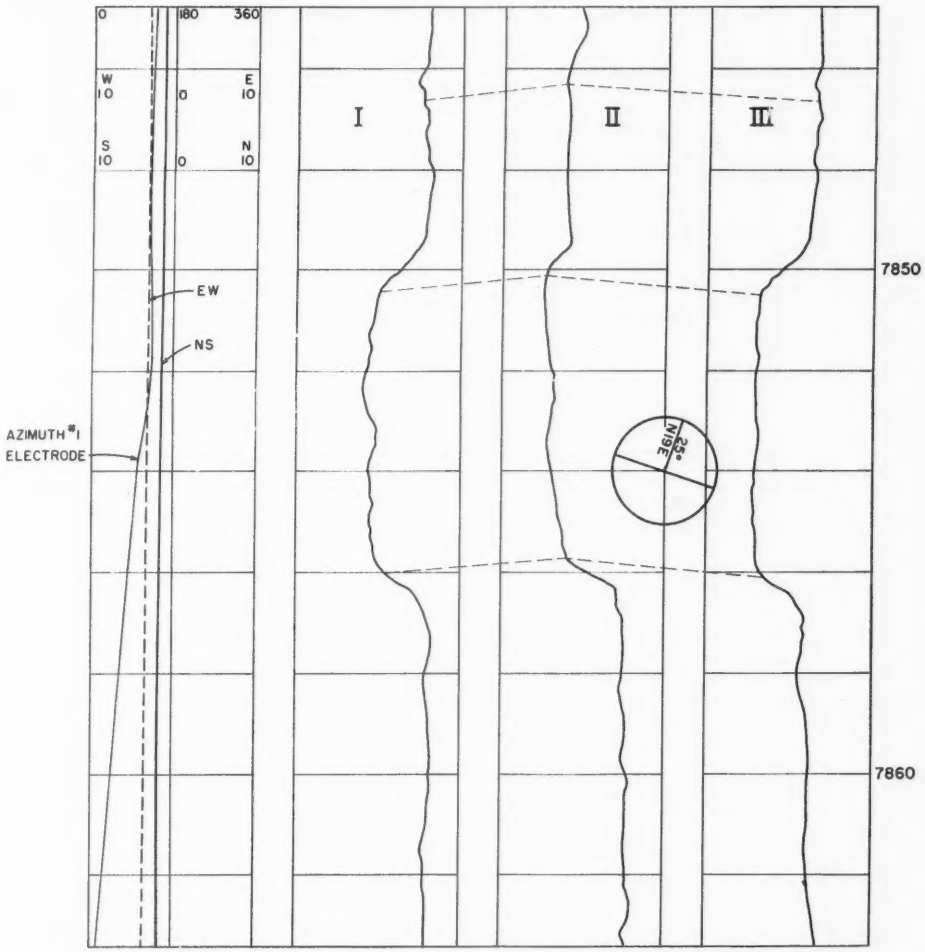


FIG. 11. Example of determination of high dip (25°). (Well B).

sistency of the results. It is seen that between about 7,300 ft and 7,800 ft the direction of the dip varies very little, and the angle of dip is comparatively high (between 30° and 50°). Above this interval, the direction of the dip is almost opposite and the angle is very low (4°–6°), which indicates an unconformity. Below the interval, another rapid change in the direction and the angle of the dip is observed, revealing, in this case, the presence of a fault.

The complete results of the dip determinations made in this well are listed in Table II.

3. Figures 13, 14 and 15 show the comparison between the dip determined by means of the dipmeter in a given well (well No. 1) and that determined by the correlation between well No. 1 and two other nearby wells (No. 2 and No. 3).

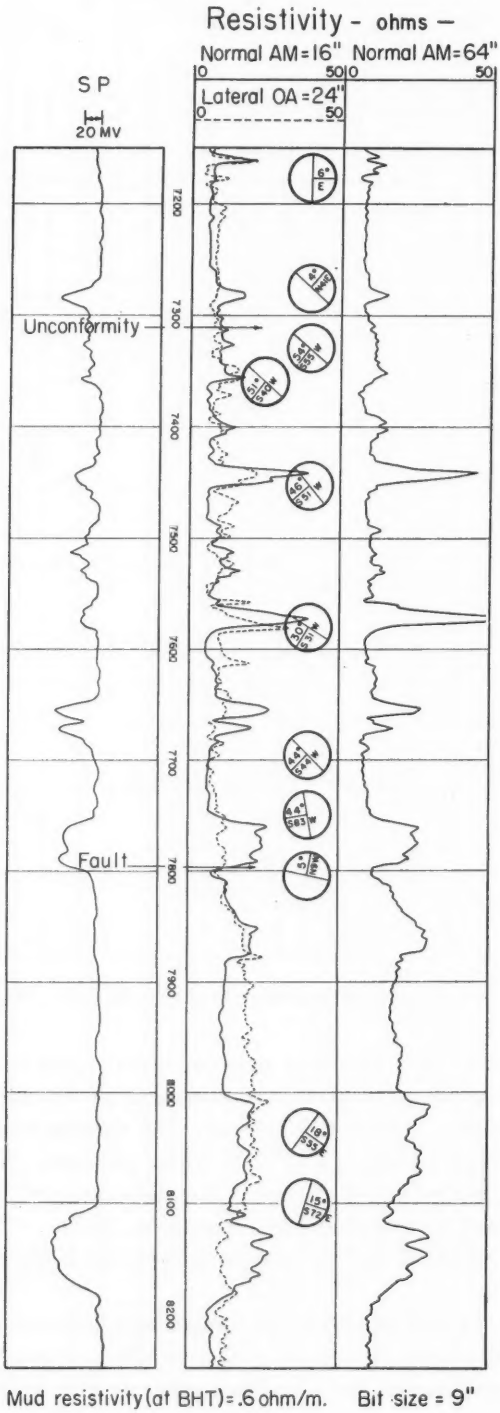


FIG. 12. Electrical log and results of dip measurements (Well B).

STATION	Depth Interval	FROM MAGNETIC NORTH: Drift Azimuth	Drift Angle	Orient No. 1	Displacement of curves in reference to I: II	III	Direction	Dip	FROM TRUE NORTH: AVERAGE DIRECTION	AV DIP	Graph of Direction
	to 1106	90	2 9	190	U3.8	D0.8	121	29	S-47-E	29	
	to 1740	315	2 5	252	U2.3	D4.0	154	40	S-16-E	40	
	to 2710	323	3 5	48	D8.0	D0.6	169	49	S-1-E	49	
	3425 to 3460	309	3 4	360	D10.7	D16.8	198	65	S-23-W	66	
				360	D13.8	D16.8	188	67			
	3935 to 3948	232	4 3	65	D15.6	D10.6	223	63	S-43-W	63	
				67	D16.4	D6.3	204	63			
	4316 to 4352	311	4 8	140	0	U6.5	198	44	S-28-W	44	
	4476 to 4480	302	4 1	96	D4.7	U1.7	195	40	S-25-W	40	
	4801 to 4807	308	4 4	112	D3.6	U6.8	187	54	S-17-W	54	
	to 4896	307	4 3	118	D3.0	U6.8	190	53	S-21-W	51	← MARKER "A"
				118	D3.0	U5.4	193	48			
	5282 to 5304	320	5 4	129	D2.3	U5.8	203	48	S-26-W	45	
				132	D1.0	U6.2	197	47			
				45	D6.6	D2.8	187	43			

FIG. 13. Well No. 1—dip determination.

Figure 13 gives the table of dip determinations made for well No. 1. The interval from 4,807 ft to 4,896 ft, where the azimuth is S21°W and the angle is 51° corresponds to the location of an electrical marker (marker *A*) on the conventional electrical curves (the elevation of marker *A* below sea level is −3,843 ft and the elevation of the well is 1,035 ft).

Figure 14 shows the relative locations of wells 1, 2 and 3 and the correlation of marker *A* between these wells.

On Figure 15, the elevation of marker A is plotted for each of the wells. The dashed lines represent the map of the interpolated contour lines for marker *A*. The solid line perpendicular to the contour lines gives the average direction of the dip, namely S26°W against S21°W found with the dipmeter in well No. 1. The angle of dip calculated from electrical marker *A* is 33° against 51° in well No. 1 as given by the dipmeter.

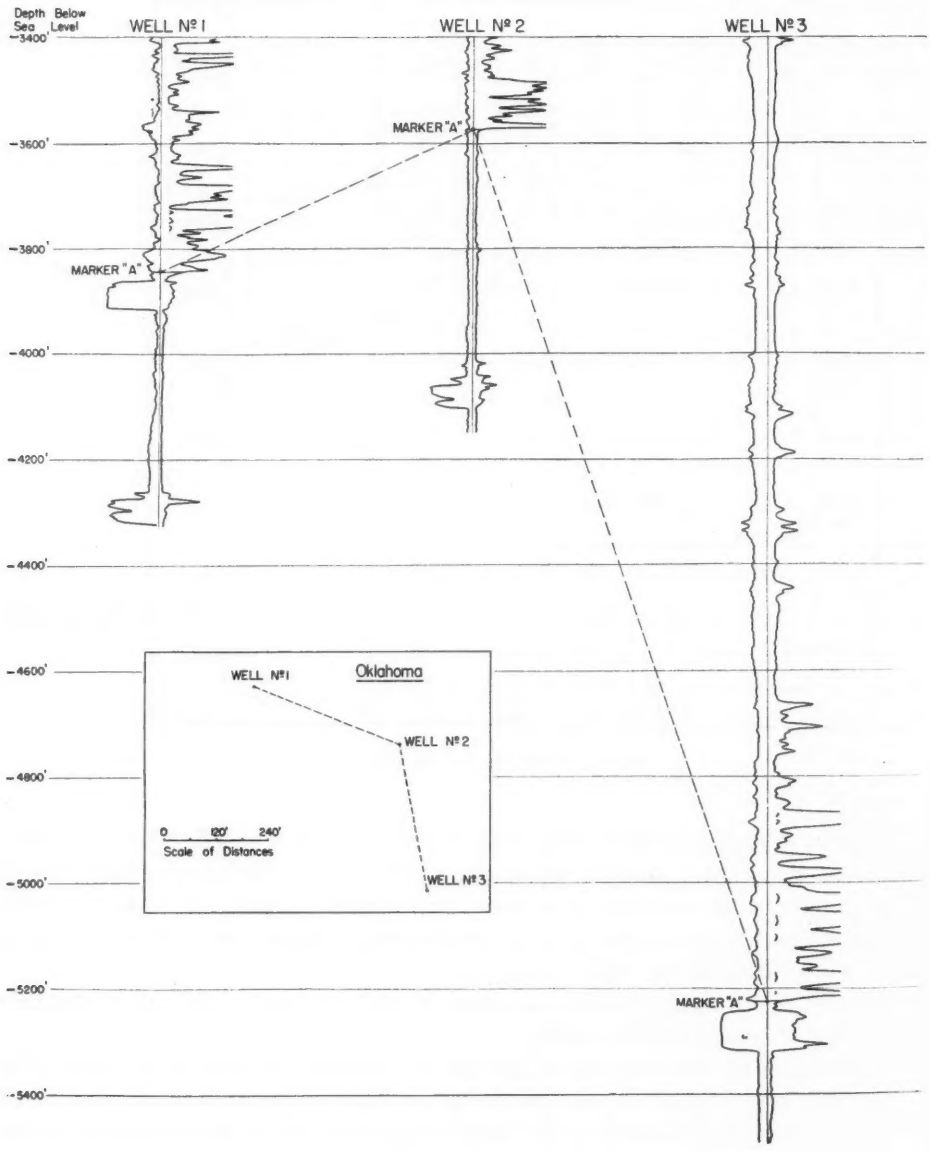


FIG. 14. Electric log correlation between three Oklahoma wells.

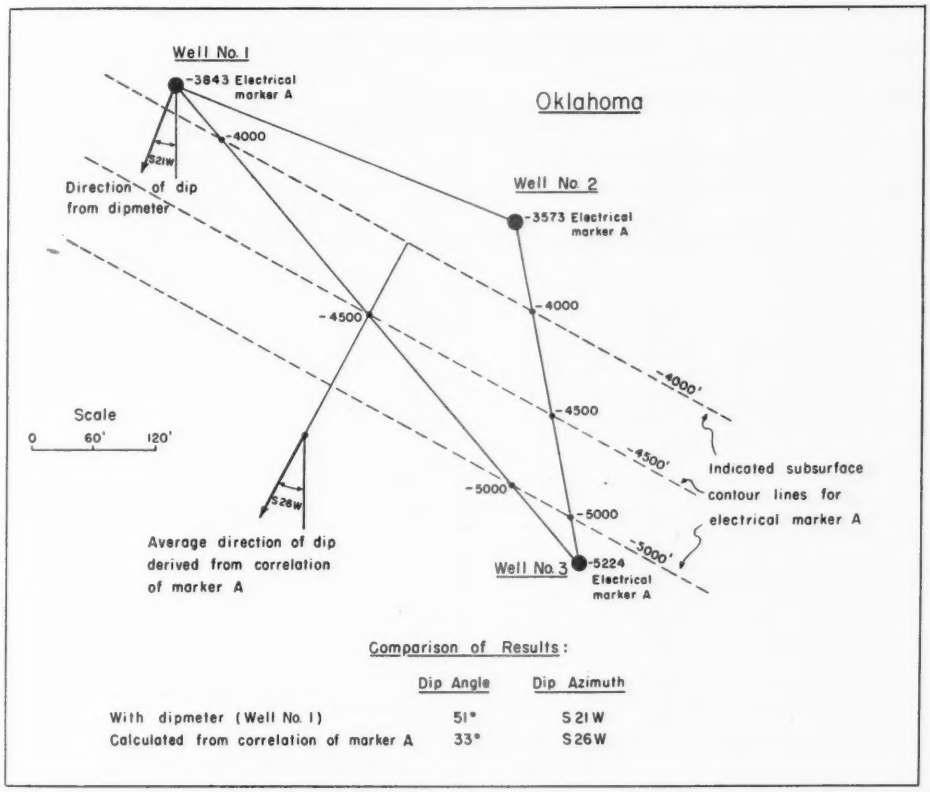


FIG. 15. Graphical determination of dip using data for electrical marker A showing comparison with dip obtained by dipmeter.

CONCLUSION

A new instrument for determining the angle and azimuth of the dip of the formations has been described, based on the correlation between curves recording electrical measurements made along the wall of a borehole in three equally spaced directions.

This instrument comprises a dipmeter system, wherein the electrical measurements are made and continuously recorded by means of three MicroLog devices and a teleclinometer system, which operates simultaneously and makes possible the continuous recording of the orientation of the instrument and of the angle and azimuth of the inclination of the borehole.

This new instrument offers the following advantages:

a) The instrument can be run in wells with a high inclination angle or in deviated wells.

b) The recording speed is appreciably greater than with the earlier instruments operating over separate short intervals of the hole.

TABLE II

DIP DETERMINATIONS (Well B—Oklahoma)

DEPTH FT	DIRECTION (AZIMUTH IN DEGREES)	DIP DEGREES
5,384	N 44 E	6
6,430	N 62 E	8
6,640	N 64 E	7
7,178	E	6
7,276	N 41 E	4
	Unconformity	
7,330	S 55 W	54
7,360	S 40 W	51
7,453	S 51 W	46
7,582	S 31 W	30
7,697	S 44 W	44
7,750	S 83 W	44
	Fault	
7,805	N 9 W	5
8,036	S 55 E	18
8,100	S 72 E	15
8,473	S 76 E	17
8,856	N 19 E	25
9,120	N 6 E	78
9,299	N 69 E	76
9,388	S 19 E	73
9,850	S 40 W	55
10,303	S 31 W	72
10,479	S 77 W	81
10,494	N 69 W	68

c) Because of the high power of resolution of the MicroLog, the curves used for correlation show a much greater amount of detail. This characteristic, in addition to the continuous recording, increases considerably the total thickness available for correlation.

d) The MicroLog curves give a sharper delineation of the boundaries, thus making the correlations easier and more accurate.

Numerous dip determinations can thus be made in a given borehole in a comparatively short time. This allows more flexibility, convenience and precision in the study of structural and related problems.

ACKNOWLEDGMENTS

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2. Doll, H. G. (1950) The MicroLog—A new electrical logging method for the detailed determination of permeable beds. *J. Petroleum Technology*, Vol. 2, pp. 155–164.
3. Doll, H. G. (1943) The SP dipmeter. *A.I.M.E.—T.P. 1547, Petroleum Technology.*
4. Schlumberger, C. & M., and Doll, H. G. (1933) The electromagnetic teleclinometer and dipmeter. *World Petroleum Congress.*
5. Stratton, E. F. and Hamilton, R. G. (1947) Application of dipmeter surveys. Presented at AIME Meeting, Tulsa, October, 1947.

PATENTS

O. F. RITZMANN*

ELECTRICAL PROSPECTING

U. S. No. 2,636,924. H. T. F. Lundberg and T. Zuschlag. Iss. 4/28/53. App. 11/1/44. Assign. Lundberg Explorations, Ltd.

Method of Geophysical Exploration. A method of geophysical prospecting in which an operator with a recording detecting instrument traverses an area in an aircraft or boat and upon locating the peak of an anomaly makes a traverse across the peak at right angles to the original traverse and marks the area.

U. S. No. 2,640,097. K. C. Crumrine. Iss. 5/26/53. App. 10/21/49. Assign. Standard Oil Development Co.

Precision Switching Assembly for Electrical Prospecting. A cam-driven switching mechanism for use in four-electrode electrical prospecting which reverses the d-c applied to the ground and in proper sequence also reverses the connections from the potential electrodes to the potentiometer.

U. S. No. 2,642,477. M. Puranen and A. A. Kahma. Iss. 6/16/53. App. 9/8/47 and 8/11/48.

Method for Inductive Prospecting. An electromagnetic prospecting system in which the ground is energized by a coil with current of low frequency which is also transmitted as a modulation component on a high-frequency carrier, the signals being picked up and the phase difference measured between the low-frequency field signal and the demodulated carrier signal.

GRAVIMETRIC PROSPECTING

U. S. No. 2,634,610. D. Silverman. Iss. 4/14/53. App. 12/19/49. Assign. Stanolind Oil and Gas Co.

Acceleration-Compensated System. A system for compensating a pendulum or gravimeter against accelerations of a transporting vehicle in which the distance of the vehicle to a fixed reference point on the earth is measured as by echo sounding or radio altimeter and the distance converted to an electrical signal which is differentiated and applied to the device as an electromagnetic compensating force.

U. S. No. 2,638,001. H. M. Zenor. Iss. 5/12/53. App. 1/9/47. Assign. Standard Oil Development Co.

Underwater Measuring Device. An underwater gravimeter having an outer case with an inner spherical oil-filled case mounted on gimbals and from which the gravimeter is suspended by gimbals.

MAGNETIC PROSPECTING

U. S. No. 2,634,393. W. I. L. Wu and V. V. Vacquier. Iss. 4/7/53. App. 8/14/44. Assign. U.S.A.

Conversion System. A system for converting alternating unequal electrical pulses from a flux-valve into unidirectional equal pulses by applying the flux-valve output to one diagonal of a bridge rectifier and taking off a signal across the other diagonal and with a potentiometer in the bridge to permit balancing.

U. S. No. 2,635,134. W. P. Jenny. Iss. 4/14/53. App. 12/12/49.

Surface Micromagnetic Survey Method. A magnetic prospecting method in which a number of recording magnetometers are suspended from a blimp and intensity measurements are made simultaneously at points several hundred feet above the ground and at points an equal distance directly above the first points.

* Gulf Oil Corporation, Patent Department.

U. S. No. 2,636,924. H. T. F. Lundberg and T. Zuschlag. Iss. 4/28/53. App. 11/1/44. Assign. Lundberg Explorations Ltd.

Method of Geophysical Exploration. For abstract see Electrical Prospecting.

U. S. No. 2,642,479. J. W. Jones. Iss. 6/16/53. App. 1/5/48. Assign. Sun Oil Co.

Device for Detecting or Measuring Magnetic Fields. A magnetic gradiometer having a pair of spaced saturable reactors excited by a-c from an oscillator in a bridge circuit so that third harmonic peaks appear in the output and having an indicating circuit sensitive to peaks of only one polarity so as to indicate the second harmonic component in the output.

SEISMIC PROSPECTING

U. S. No. 2,634,398. R. G. Piety. Iss. 4/7/53. App. 11/24/50. Assign. Phillips Petroleum Co.

Method of Eliminating an Undesired Component of Seismic Waves. A seismograph mixing system in which the signal from one detector is inverted and delayed by the time required for the surface wave to traverse the distance between the detectors.

U. S. No. 2,635,705. P. E. Haggerty. Iss. 4/21/53. App. 10/22/48. Assign. Texas Instruments Inc.

Method and Apparatus for Seismic Prospecting in Which Seismic Waves are Used to Modulate a Sonic or Supersonic Carrier Wave. A seismic recording method in which a continuous sonic or supersonic wave is passed through the earth and the modulation effect of an explosive wave is detected.

U. S. No. 2,636,160. G. B. Loper and S. N. Heaps. Iss. 4/21/53. App. 8/29/49. Assign. Socony-Vacuum Oil Co., Inc.

Vertical Component Low-Frequency Geophone. A moving-coil permanent-magnet type of electromagnetic seismometer in which an axial magnet has an eccentric pole piece and air gap in which the coil is suspended on a cantilever beam with a helical supporting spring.

U. S. No. 2,637,839. R. G. Piety. Iss. 5/5/53. App. 4/20/48. Assign. Phillips Petroleum Co.

Rotational Seismometer. A reluctance-type rotational seismometer having an axially-suspended cylindrical permanent magnet and a series of pole pieces adjacent to armatures on the case.

U. S. No. 2,638,176. W. W. Doolittle. Iss. 5/12/53. App. 2/23/49. Assign. Stanolind Oil and Gas Co.

Marine Seismic Surveying. A method of seismic prospecting in water-covered areas in which a seismic spread having spaced floats along the cable is towed through the water and stopped on location and the shot made when the detectors between floats have sunk to below the depth of surface noise.

U. S. No. 2,638,402. B. D. Lee. Iss. 5/12/53. App. 6/9/47. Assign. The Texas Co.

Seismic Prospecting. Apparatus for scanning a seismograph record having individual optical scanning means for each trace, the signals being combined in pairs with variable time-phase differences introduced in the scanning and the amplified signals combined with at least one signal reversed.

U. S. No. 2,638,578. R. G. Piety. Iss. 5/12/53. App. 2/11/52. Assign. Phillips Petroleum Co.

Seismometer. A capacitive seismometer having helical plates on the inside of a cylindrical case and interposed helical plates on a centrally-suspended moving system which also carries an armature in the field of a coil so that the condenser spacing may be adjusted electrically.

U. S. No. 2,640,186. A. F. Hasbrook. Iss. 5/26/53. App. 6/13/49. Assign. Olive S. Petty.

Seismic Surveying. A shot-moment recording system in which the break initiates oscillation of a damped-wave oscillator whose output pulses are shaped to provide a signal from which the shot moment may be obtained through interference.

U. S. No. 2,640,187. A. F. Hasbrook. Iss. 5/26/53. App. 6/13/49. Assign. Olive S. Petty.

Seismic Surveying. A shot-moment recording system in which the break initiates a circuit generating a series of pulses each of which is given a predetermined different time delay so that the initial break may be obtained through interference.

U. S. No. 2,641,749. F. L. Lawrence. Iss. 6/9/53. App. 12/15/51. Assign. Standard Oil Development Co.

Time Break Recording in Seismic Prospecting. A system for recording the make of the shot-firing circuit, the break of the shot-firing circuit, and the up-hole impulse on a single trace and using a thyratron to cut out the shot-firing circuit after the time break.

U. S. No. 2,642,146. J. P. Woods. Iss. 6/16/53. App. 9/20/50. Assign. The Atlantic Refining Co.

Shot Hole Array for Eliminating Horizontally Traveling Waves. A shot array for seismic prospecting having two parallel straight-line arrays of unequal lengths with the shorter array being 0.76 π times the wave length of the horizontally-traveling waves to be suppressed, or having two concentric circular arrays each having at least 8 simultaneous shots with the circumferential length of one being 0.76 π and the other 1.76 π times the wave length to be suppressed.

U. S. No. 2,643,367. C. G. Cruzan. Iss. 6/23/53. App. 1/5/48. Assign. Phillips Petroleum Co.

Magnetostriction Seismometer. A seismometer having a magnetostrictive bar extending between the poles of a horseshoe magnet with an inertia mass suspended horizontally on a cantilever arm from the center of the bar and with pick-up coils on each half of the bar.

U. S. No. 2,643,869. J. Clark. Iss. 6/30/53. App. 1/15/48.

Accelerometer. A variable air-gap seismometer in which the air-gaps are in the magnetic circuits of two transformers whose primaries are excited by a-c and whose secondary voltages are measured.

WELL LOGGING

U. S. No. 2,633,783. C. Laval, Jr. Iss. 4/7/53. App. 2/13/50.

Apparatus Adapted to Provide Photographic Records of Wells and the Like. A camera for use in a well and having a lamp in front of a stereoscopic camera, electric power being supplied from the surface to advance the film and to charge a condenser which discharges through the lamp when the power is interrupted.

U. S. No. 2,636,383. K. R. More and W. G. Middleton, Jr. Iss. 4/28/53. App. 1/23/48. Assign. Phillips Petroleum Co.

Well Bore Measuring and Fluid Metering Device. A well-logging apparatus having three caliper arms and a central impeller-type flowmeter with the caliper and the flowmeter signals electrically integrated so that total flow is recorded.

U. S. No. 2,637,206. E. R. Atkins, Jr. Iss. 5/5/53. App. 10/13/49. Assign. Union Oil Co. of Calif.

Flowmeter. A well flowmeter for measuring the flow velocity of an electrically non-conducting fluid in which a momentary electrostatic charge is placed on a portion of the fluid as it enters the instrument and detected as it leaves the instrument with the time recorded for the charged fluid to traverse the known distance in the instrument.

U. S. No. 2,639,512. J. C. Legrand. Iss. 5/26/53. App. 9/26/47. Assign. Schlumberger Well Surveying Corp.

Drill Hole Gauge. A caliper-logging apparatus in which the caliper arms move an associated core or coil and changes in inductance are observed.

U. S. No. 2,640,161. S. Krasnow and M. J. Test. Iss. 5/26/53. App. 10/1/41 and 5/19/48. Assign. Schlumberger Well Surveying Corp.

Energizing System for Borehole Radioactivity Apparatus. A power supply for a radioactivity logging apparatus which is supplied with low-voltage a-c from the surface and signals the output of a radioactivity detector to the surface by d-c.

U. S. No. 2,640,271. F. G. Boucher. Iss. 6/2/53. App. 4/27/48. Assign. Standard Oil Development Co.

Well Logging Method and Apparatus. A well-logging apparatus having centering springs at the top and bottom of the sonde which has three azimuthally-spaced profiling arms whose respective extensions are separately recorded at the surface together with the azimuthal orientation and inclination of the sonde.

U. S. No. 2,640,275. F. G. Boucher. Iss. 6/2/53. App. 4/29/49. Assign. Standard Oil Development Co.

Oriented Dip and Strike Indicator for Boreholes. A well-logging apparatus having centering springs at the top and bottom of the sonde which has three azimuthally-spaced profiling arms at the level of one set of centering springs arranged to electrically record at the surface the distance from the center of the sonde to the borehole wall together with the azimuthal orientation and inclination of the sonde.

U. S. No. 2,640,869. C. W. Zimmerman. Iss. 6/2/53. App. 6/3/50. Assign. Schlumberger Well Surveying Corp.

Temperature Compensated Susceptibility Logging System. An electromagnetic logging system having a solenoid in a bridge circuit with one arm containing a resistance whose temperature coefficient of resistance corrects for temperature variations in the inductance of the solenoid.

MISCELLANEOUS

U. S. No. 2,634,317. J. A. Marchand and J. Platis. Iss. 4/7/53. App. 2/24/50.

Apparatus for Determining the Orientation of Underground Strata from Core Samples. A device for rotating a core sample between the poles of a pick-up coil whose output is fed to an amplifier and recording galvanometer and an optical system for recording on the same film the instantaneous orientation of the sample.

U. S. No. 2,635,349. P. M. Green. Iss. 4/21/53. App. 12/2/50. Assign. Socony-Vacuum Oil Co., Inc.

Well-Surveying Inclinometer. An inclinometer having a pair of spherical cells partially filled with mercury and with resistors along great circles on the spheres to electrically indicate inclination components with respect to a direction gyro and an integrator at the surface whose output indicates the horizontal components of drift distance.

U. S. No. 2,636,569. A. L. Smith. Iss. 4/28/53. App. 9/29/47.

Means for Separating Gas from Drilling Muds and Analyzing Same. An apparatus for separating gas from drilling mud by passing a sample through a diluent and analyzing the gas released with a combustion meter.

U. S. No. 2,637,998. J. H. Ramser. Iss. 5/12/53. App. 11/14/46. Assign. The Atlantic Refining Co.

Apparatus for Determining Well Pressures. A bottom-hole pressure gauge having a Bourdon tube with an arm which moves the plate of a triode vacuum tube in an oscillator circuit whose frequency is observed.

U. S. No. 2,63,671. K. Ramsey. Iss. 5/19/53. App. 6/14/51. Assign. The Geolograph Co., Inc.

Apparatus for Translating and Plotting Log Charts from Drilling Time Charts. A curve-drawing mechanism for converting a well drilling log having variable footage plotted against linearly-increasing time to a chart showing variable drilling time plotted against linearly-increasing depth.

U. S. No. 2,639,615. D. H. Clewell and C. F. Rust. Iss. 5/26/53. App. 3/11/47. Assign. Socony-Vacuum Oil Co., Inc.

Barometric Measurement of Elevation. A system of barometric elevation surveying in which variations in barometric pressure at a base station are transmitted by radio to a mobile station where the radio signal and the local barometric pressure are recorded on a chart.

U. S. No. 2,641,922. A. L. Smith. Iss. 6/16/53. App. 10/16/44 and 8/30/50.

Core Analysis. A core analysis apparatus having a flexible container into which the core may be placed and flushed with liquid, the core being broken by flexing the container and released gas observed.

SELECTED LIST OF U. S. PATENTS ISSUED DURING THE SECOND QUARTER OF 1953

Patent No.	*Subject**	*Patent No.*	*Subject*	*Patent No.*	*Subject*
2,633,639	444	2,635,224	68	2,636,964	484
2,633,645	520	2,635,225	460	2,636,990	236
2,633,737	168	2,635,232	316	2,636,992	420
2,633,738	288	2,635,329	140	2,636,994	308
2,633,750	148	2,635,349[a]	520, 68	2,637,019	168
2,633,783[a]	280	2,635,372	444	2,637,021	312
2,633,800	136	2,635,406	360	2,637,023	316
2,634,067	16	2,635,453	428	2,637,024	312
2,634,106	80	2,635,461	412	2,637,025	316
2,634,317[a]	84, 220	2,635,462	412	2,637,027	316
2,634,335	224	2,635,465	428	2,637,028	316
2,634,374	308	2,635,467	16	2,637,111	200
2,634,391	16	2,635,468	460	2,637,205	428
2,634,393[a]	232	2,635,469	16	2,637,206[a]	148, 144
2,634,398[a]	356	2,635,705[a]	76, 360	2,637,207	148
2,634,411	312	2,636,075	32	2,637,210	288
2,634,412	312	2,636,127	140	2,637,294	16
2,634,413	316	2,636,134	288	2,637,295	16
2,634,608	200	2,636,160[a]	376	2,637,495	68
2,634,609	196	2,636,161	16	2,637,561	224
2,634,610[a]	180	2,636,166	312	2,637,619	324
2,634,612	200	2,636,167	312	2,637,785	224
2,634,702	216	2,636,383[a]	44, 144, 148	2,637,823	484
2,634,721	288	2,636,386	484	2,637,839[a]	376
2,634,908	196, 68	2,636,387	260	2,637,846	316
2,634,909	68	2,636,478	148	2,637,848	312
2,634,925	16	2,636,479	148	2,637,907	428
2,635,032	324	2,636,561	48	2,637,914	16
2,635,034	324	2,636,569[a]	252	2,637,998[a]	288
2,635,038	168	2,636,673	16, 68	2,638,000	200
2,635,134[a]	232	2,636,674	68	2,638,001[a]	180
2,635,149	224	2,636,698	16	2,638,176[a]	360
2,635,152	16	2,636,699	16	2,638,268	68
2,635,195	68	2,636,924[a]	232, 124	2,638,335	428, 4

* A key to the subject classification system will be found in *Geophysics*, Vol. 12, pp. 256–264 (April, 1947).

[a] Abstracted on preceding pages of this issue.

Patent No.	*Subject*	*Patent No.*	*Subject*	*Patent No.*	*Subject*
2,638,402[a]	360, 356	2,639,978	168	2,641,751	484
2,638,492	160	2,640,097[a]	124	2,641,754	16
2,638,493	68	2,640,110	484	2,641,841	484
2,638,507	224	2,640,158	308	2,641,843	16
2,638,551	308	2,640,161[a]	304	2,641,922[a]	88
2,638,552	308	2,640,165	484	2,641,924[a]	88
2,638,553	308	2,640,170	484	2,641,926	428
2,638,556	4	2,640,186[a]	388	2,641,930	460
2,638,577	484	2,640,187[a]	388	2,641,931	460
2,638,578[a]	376	2,640,190	140	2,642,146[a]	360, 136
2,638,579	16	2,640,191	316	2,642,223	68
2,638,585	316	2,640,269	200	2,642,477[a]	132
2,638,586	316	2,640,271[a]	44, 520	2,642,479[a]	232
2,638,587	316	2,640,275[a]	520, 44	2,642,482	140
2,638,590	312	2,640,356	148	2,642,535	236
2,638,671[a]	100	2,640,389	196	2,642,536	168, 196
2,638,683	216	2,640,542	392	2,642,539	308
2,638,778	496	2,640,690	260	2,642,541	308
2,638,779	496	2,640,866	160	2,642,545	76
2,638,780	428	2,640,869[a]	128	2,642,562	108
2,638,781	428	2,640,870	168	2,642,737	168, 188
2,638,782	16	2,640,886	484	2,642,738	412
2,638,783	188	2,640,888	484	2,642,740	428
2,638,784	460	2,640,889	484	2,642,741	428
2,638,786	16	2,640,935	236	2,642,742	460
2,638,801	48	2,640,936	308, 148	2,643,071	224
2,638,811	416	2,640,977	200	2,643,130	224
2,638,981	48	2,640,982	312	2,643,286	12
2,639,089	68	2,640,983	316	2,643,341	236
2,639,090	68	2,640,984	316	2,643,342	236
2,639,189	460	2,641,034	200	2,643,344	308
2,639,210	4	2,641,060	216	2,643,348	68
2,639,257	484	2,641,061	444	2,643,354	16
2,639,305	460	2,641,131	288	2,643,367[a]	376
2,639,316	140	2,641,133	16	2,643,374	312
2,639,333	224	2,641,134	16	2,643,457	16
2,639,389	308	2,641,185	136	2,643,543	496
2,639,390	308	2,641,407	68	2,643,547	16
2,639,420	316	2,641,409	12, 308	2,643,574	416
2,639,422	316	2,641,413	40	2,643,819	68
2,639,423	316	2,641,420	224	2,643,820	68
2,639,424	316	2,641,457	4	2,643,821	68
2,639,426	316	2,641,458	4	2,643,858	404
2,639,512[a]	44	2,641,523	324	2,643,869[a]	4
2,639,514	180	2,641,655	224	2,643,870	4, 68
2,639,612	448	2,641,656	224	2,644,117	32
2,639,615[a]	444	2,641,688	316	2,644,123	108, 436
2,639,616	288	2,641,710	168, 308	2,644,154	316
2,639,770	48	2,641,719	288	2,644,155	316
2,639,964	324	2,641,742	288		
2,639,965	324	2,641,749[a]	388, 488		

REVIEWS

REVIEWS COMMITTEE

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Guidebook of the Joint Annual Meeting, published by Houston Geological Society, Available from Fred L. Smith, 514 Esperson Building, Houston 2, Texas. Price $5.25 by mail.

The Houston Geological Society prepared the Guidebook for the Joint Annual Meeting of the AAPG, SEPM and SEG held in Houston, Texas in March, 1953. The volume contains six articles under the heading of General Geology and twenty three papers on oil fields.

The first article "A Half Century of Gulf Coast Geology" by John M. Vetter summarizes the historical development of oil production in the Gulf Coast and gives some statistics on accumulated production. It is interesting to note briefly the development of oil production. In the period 1901 to 1923 surface indications were the chief exploratory method and 40 domal structures were discovered. During the period 1923 to 1929 geophysical exploration entered the scene through the vehicles of the torsion balance and refraction seismograph. In addition micropaleontology became an important factor. During this period 70 domal structures were found. In the following period, 1930 to 1950, the torsion balance gave way to the gravity meter and the refraction seismograph to the reflection seismograph. This resulted in an accelerated rate of discovery during which period 300 structures were found, including deep domes and faulted segments. Mr. Vetter predicts that the period beginning during the year 1950 will witness the development of offshore structures and of updip pinchouts in the Gulf Coast proper.

To date about five billion barrels of oil have been produced and an equivalent amount is considered to be in reserve. Also ten trillion cubic feet of gas have been produced and 40 trillion are in reserve. Furthermore, the search for oil on salt domes has contributed to the mining of sulphur and 100 million tons of sulphur have been produced.

W. W. Patrick summarizes statistics of salt domes. He lists 35 shallow domes (salt less than

2,500 ft. deep) in Texas, ten intermediate domes and eight deep domes where the salt depth is greater than 6,000 ft. His paper also includes a table of the wells that have penetrated the salt.

The third paper in the section on General Geology is written by the Field Trip Committee and is entitled "Geology of the Gulf Coast." The paper first describes the stratigraphy of the Gulf Coast with the normal breakdown into the Wilcox, Yegua, Frio and Miocene producing belts. In addition attention is given to the phenomenon of thickening toward the Gulf along "hinge" lines.

The second portion of this paper is devoted to regional structure and very aptly lists the Gulf Coast Homocline as the major structure of the area. The normal fault systems of the area are quite obviously attributed to the continuing development of this major structure.

C. W. Stuckey gives an excellent exposition on the Wilcox, Yegua, Frio and Miocene formations in his paper "Tertiary Stratigraphy of the Texas Gulf Coast." The Houston area is the basis of this discussion. Correlations of the individual members are included and their lateral and longitudinal thickening is described.

The section is concluded by the presentation of "Some Gulf Coast Fossils" by the Field Trip Committee and Perry Olcott presents an abstract entitled "Structures Controlling Accumulation."

The remainder of the volume contains 23 papers on oil fields, including ten on deep domes, nine on shallow domes, three on fault segments and one on a residual anticline. Each of the papers has the same format. The general stratigraphy, structure and production record of the field is presented. The group of papers affords an excellent opportunity to study Gulf Coast structures and their production record in the light of the most recent subsurface data. If any paper can be singled out it would be the paper on Boling Field by Ralph B. Cantrell, which is of peculiar interest because of the diversity of structures on this shallow salt dome. Any criticism of this section could be aimed at the limited amount of data on the fault segment type of structure although this is undoubtedly because of the relatively small amount of production that is obtained from this type of structure as compared to the salt dome structures.

In conclusion the Committee is to be commended for a very succinct presentation of Gulf Coast geology. The maps and the discussions are easy to read, fulfilling the general requirement that the reader be allowed to gain the "maximum amount of information in the minimum amount of time."

NELSON C. STEENLAND

"On the Interpretation of Gravity Data," by A. Van Weelden. *Geophysical Prospecting*, Vol. 1, No. 2, June, 1953.

This paper is the presidential address delivered at the Second Annual Meeting of The European Association of Exploration Geophysicist which was held in Paris in May, 1953.

Van Weelden undertakes to discuss two aspects of the interpretation of gravity data. The first is the rather belabored argument between the so-called mathematical school of interpretation and the geological school of interpretation. The first school is defined as that group which uses grid-template methods of calculations of second derivatives, residuals, ar projections. Van Weelden recalls the ambiguity of the gravity data and concludes that it is fallacious to calculate a unique interpretation. He rules out the grid template methods principally on this basis. However, he does recognize that the grid template methods are very easy and quick and that relatively unskilled help may be employed in such calculations. He also recognizes that some anomalies are very vividly resolved by machine calculation.

But the author is a confirmed member of the geological school and states his case for the so-called graphical method of interpretation. He favors this more "hand-tailored" method because it enables the gravity interpreter to employ other geological and geophysical evidence which enables him, in many instances, to circumvent the problem of ambiguity. The reviewer cannot help but remark that, inasmuch as both methods have their advantages, it seems quite obvious that both methods are to be employed.

The second aspect of the interpretation which Van Weelden discusses is one subject which he finds deplorable and which many geophysicists can hardly believe still exists. Apparently there are

still instances where the gravity interpreter is asked to analyze his ambiguous data without being able to resort to other geological and geophysical evidence. Furthermore, there appear to be frequent instances when, if first results are found to be incorrect, the interpreter is not allowed to incorporate the new evidence but the method is ridiculed and no provisions are made for second or third interpretations. This is certainly an unreasonable process and Van Weelden makes a plea for the more mature and up to date attitude toward gravity interpretation.

This article appears in the second number of the first volume of the new magazine *Geophysical Prospecting*, the official journal of the European Association of Exploration Geophysicists. Several other articles from the first and second numbers of this volume are currently being reviewed for the next issue of *Geophysics*. The material of these two numbers has been excellent, exhibiting a very high technical level. Future numbers are certainly to be welcomed and congratulations are due our fellow European Society on their new publication.*

NELSON C. STEENLAND

"Magnetic Properties of Rocks," by J. M. Bruckshaw. *Nature*, vol. 171, no. 4351, pp. 500–502, March 21, 1953.

The puzzling problem of reversed magnetization of sedimentary and igneous rocks was the theme of a geophysical discussion at a joint meeting of the Royal Astronomical Society and the Geological Society in London on January 23, 1953, under the chairmanship of Prof. E. C. Tilley of the Department of Mineralogy and Petrology at Cambridge University.

To state it briefly, the problem is to explain numerous anomalous cases of magnetized rocks in nature for which the magnetization is at nearly 180° to the normal direction, that is, the direction of the earth's present magnetic field. Two hypotheses have been advanced to explain this phenomenon. The one is that the direction of the earth's field has varied widely and frequently in its past geologic history. The other is that a reversed magnetization may arise from certain inherent properties of the rock constituents, such as the presence of two magnetic constituents with widely different Curie temperatures, so that the second constituent may be demagnetized by the field due to the first.

The paper under review is a report by one of the participants, Dr. J. M. Bruckshaw, who summarizes the contents of the contributions presented. It can hardly therefore be abstracted or summarized further and is highly recommended reading for those interested in the current status of this peculiar problem.

I shall merely quote the closing paragraph: "Summarizing, Prof. Tilley said that many outstanding questions still remain and further data are necessary on sediments and igneous rocks. In particular, a knowledge of the accessory minerals is essential."

THOMAS A. ELKINS

"Das Normalfeld der Schwere für Deutschland" (Theoretical Gravity for Germany). By Von K. Sellien. "Das Rössigersche Normalfeld der Vertikalintensität und seine zeitliche Anderung" (Theoretical Magnetic Field (Δz) According to the Roessiger Method, and its Secular Variation), by Von E. Thiele. Published by Geophysikalisches Institut Potsdam, No. 5, 1952.

These two articles are reviewed as a unit because of their importance to those correcting gravity and magnetic data obtained from geophysical surveys in this country.

The first report presents a new series of theoretical gravity values for Germany. The values used for the constants are based in part on a total of 143 pendulum stations occupied during the last two decades in Germany. A comparison is made also between values calculated according to several geodetic formulas, including Helmert (1901), Heiskanen and Cassinis (1930), and Heiskanen (1938).

* Further information on the European Association and on the availability of its journal, *Geophysical Prospecting*, to S.E.G. members may be found on pp. 765–66 of the July, 1953 *Geophysics* and on advertisers' page 40 of this issue.

The results are summarized in tabular form, as well as on a map showing the theoretical gravity values according to formula 3 derived in this report, and compared with Helmert's formula. The difference, particularly in the northern portion of Germany, is appreciable.

The results of the calculations of the theoretical value of the vertical component of the earth's magnetic field are presented in the record report together with a map showing the changes between 1936 and 1950. The results are also summarized in tabular form.

RICHARD A. GEYER

"Methods of Determination of the Average Resistivity of a Two Layered Medium," by Lachlan Gilchrist, A. R. Clark, and Ben Bernholtz, *Canadian Mining Journal*, v. 71, no. 1, pp. 55–64, 1950.

The authors present the methods that they have used in applying electrical techniques to exploration in the Canadian Shield. They discuss three subjects:

1. The significance of stake resistance in resistivity measurements. They argue that if the stake resistance of the two current electrodes is not the same, for instance, in the Wenner or Schlumberger configuration, that pseudo-anomalies will be present even in homogeneous media. Their argument is not convincing and their terminology confusing. This subject is well treated by Sunde.*

2. The measurement of resistivity near and between drill holes. They have used the conventional two-electrode logging system in which the stationary electrode, instead of being placed at the surface, is lowered to various depths in an adjacent hole. Because of the nearness of the potential electrode to the current electrode in each pair, the resistivity values measured reflect the near hole resistivities. Little information was obtained about the rock between the drill holes.

3. The use of multiple electrode arrays. Single line, central line and central point electrode arrays are discussed. A field example of their use is presented.

PAUL C. WUENSCHEL

"Oil Prospecting With the Radioactive Method," by Hans Lundberg and George Isford. *World Petroleum*, Vol. 24, No. 7, July 1953, p. 40.

The use of the scintillation detector for oil prospecting has been developed by Lundberg Explorations, Limited and numerous articles have appeared, mostly in publications outside of the technical journals. For instance *Fortune Magazine* described his method in some detail. The present article reproduces some profiles over the Redwater oil field in Alberta, Canada together with several profiles across a river in mid-continental United States showing the effect of the water and showing the general difference in level of intensity from one side of the stream to the other. The two principal purposes of the article are to illustrate the improved recordings which have resulted from the use of a scintillometer with a longer time constant and to give a revised explanation of these radioactive anomalies.

It is readily conceded in the article that the gamma rays that are recorded in the surveys are from the "upper two or three feet of surface." Previous articles attributed this phenomenon to the upward movement of ground water over oil pools inasmuch as the ground water was "capable of dissolving radium since its sulfates had been reduced by hydrocarbons present in small amounts." However, now that it has been learned that it is difficult to assume any upward movement of ground waters a theory of "diffusion" is presented by which the area "above the hydrocarbon layer becomes gradually very low in chlorides."

By the author's own admission the justification of the use of the radioactive method depends entirely on empirical results over established oil production, because there are practically no experimental data with which to establish the origin of these anomalies. That being the case, it seems in

* *Earth Conduction Effects in Transmission Systems*, by E. D. Sunde, D. Van Nostrand Company, New York, 1949, 367 pp., $7.65.

order to present a wealth of statistics on the results over established oil producing areas instead of a handful of profiles over one particular oil field.

NELSON C. STEENLAND

"Mapping Water-Saturated Sediments by Sonic Methods," by W. O. Smith and Herbert B. Nichols. *The Scientific Monthly*, Vol. 77, No. 1, July 1953, pp. 36–41.

This article is a popularly written description of recent investigations of the thickness of silts and recent sediments over bedrock in water covered areas. The basic equipment is similar to the familiar Sonar (Echo Sounding or Fathometer) equipment but considerable modification was required. The principal changes were in the use of lower frequencies and of higher power.

The original equipment which operated at a frequency of 50 kilocycles did not penetrate very well. It was found that frequencies of 15 kilocycles or lower would penetrate sediments of medium consistency, i.e., fine silt and clay having a water content of 40 to 50%.

The paper described three applications of the equipment to the mapping of the thickness of silt and recent sediments over bedrock.

At Lake Mead (the reservoir above the Hoover Dam in the Grand Canyon), maps were made of the thickness of sediments which have accumulated since the reservoir began to fill. In this case a check was available on the bedrock topography because the area had been mapped by aerial photography before water entered the reservoir. The essential results of this investigation are that slightly over two billion tons of sediments have accumulated and that these now occupy approximately 5% of the reservoir storage space. The anticipated life of the reservoir is approximately 445 years.

An investigation of sedimentary thicknesses in Lake Michigan in the vicinity of the Navy Pier at Chicago was made because of plans for a very large water supply and purification plant which will require a tunnel under the lake. This work was done with equipment operating at a frequency of 11 kilocycles. In this work buried valleys in the bedrock were found with as much as 130 feet of silt. These channels would be very important in planning any tunnel in order that it be kept at sufficient depth to remain in bedrock throughout its length.

In the Bay of Fundy a re-examination of the tidal power project is under consideration. The sonic method was used to determine the thickness of silt and depth to bedrock in areas where dams have been proposed. It was known from cores that the overburden thickness might be of the order of 100 to 150 ft, consisting of glacial till having a water content of 20 to 40% and composed of silt, fine sand and clay with some gravel. For this survey the equipment was redesigned to use greater power and a "considerably lower" (but unspecified) frequency. A very detailed survey was made consisting of many profiles and spaced 500 to 1,000 ft apart and with cross tie lines. Elevation control was needed because of the large tidal variation (18–27 ft); this was obtained by radio contact with shore stations at which the height of the tide was read. The work showed absence of clay sediments in the areas where dams were proposed, which was a pleasant surprise.

It appears from this work that it is quite feasible to map the top and bottom of relatively soft sediments under water covered areas by the use of relatively high frequency impulses. It would seem that the same general methods should have many applications in engineering and construction operations. The work described was done primarily by the U. S. Geological Survey but there were important contributions from the Bureau of Ships, the Navy Electronics Laboratory, The Bureau of Ordnance and the Scripps Institute of Oceanography.

L. L. NETTLETON
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A MAJOR OIL COMPANY'S SAFETY PROGRAM*

CHAS. A. MILLER†

A major oil company's Safety Program embraces so many ramifications that I feel compelled to make it clear at the outset that to give you a real picture of what our Safety Program encompasses would require much more time than is allotted me here today.

One of our employees working for the Geophysical Division once said, "I raised my family on dynamite." As a parallel to this, I could say, "I raised my family on gasoline," and I am sure that there are those who would also say that they raised their families on water. We have heard so many times the statement that the handling of and working around dynamite is dangerous; likewise with gasoline, but water—no, there is no danger! I am sure that with serious thinking on your part you will agree with me that this is an erroneous statement, for water perhaps has been responsible for more accidental deaths than all dynamite and gasoline put together. They are all safe if safe principles and practices are followed. The point I want to make is that all jobs are dangerous in some form or other if we assume an unsafe attitude, but with a safe attitude—a firm belief in safety—then we are reasonably safe in most every phase of human endeavor.

Since safety is a human and economic factor involving our everyday activities, whether it be in industry, on the highway, in the home or at school, it is a subject of paramount importance to all regardless of your position in life. We are all indeed human beings and a human being can be a worker, a supervisor, a manager or a president and—say what you want—the fact remains that the attitude of these individuals will be the answer to a good or bad Safety Program. What will change an attitude for a certain individual will perhaps have no effect on another. Sympathy, fear, grief, prestige and economic gain or loss are some of the many factors in changing unsafe attitudes to safe attitudes.

The Safety Program of The Texas Company is somewhat unusual in that it not only embraces the activities of all our operating departments, but right at this moment functions throughout almost every little town and hamlet in the 48 states of this nation and certain operations in Canada.

I think it is generally conceded by those engaged in accident prevention that while safety inspection of physical equipment is important, of greater importance are the educational aspects of a Safety Program that has as its major objective the development of safety consciousness and favorable, or safe, attitudes. Today, safety is largely a question of human engineering, or the adjustment and control of human behavior. We are constantly seeking ways to prevent accidents, and when we prevent accidents from occurring we naturally and automatically eliminate the personal injuries and property damage that result from accidents.

Safety programs are not built from the bottom up—instead, from the top down. Therefore, I shall start with the attitude of our management, who in most cases started from the ranks, and the fine cooperation and support they have given this far-reaching Safety Program. It is obvious that our Safety Program as we know it today would be non-existent had it not been for the attitude of our management—an attitude that reflected down through the ranks—that they were sincere in their support of a program that prevented the loss of life, eliminated pain and suffering and reduced accident destruction to a minimum.

In the time allotted to me, it will not be possible to discuss in detail the numerous phases and applications of our general Safety Program. In the interest of time, therefore, we will discuss briefly the following phases:

1. Safety Meeting Program, including the training of Safety Chairmen and Secretaries.
2. First Aid Training Program, including the training of First Aid Instructors.
3. The publication of our safety magazine, the *Texaco Safety Digest*.

* Text of an address presented at the Annual Meeting of the Society at Houston on March 26, 1953. Manuscript received by the Editor June 17, 1953.

† Industrial and Public Relations Department, The Texas Co., Houston, Tex.

4. Statistical analysis, including the study of personal injury and automotive accident frequency, to determine corrective procedures and stimulate these corrective procedures by means of contests and awards.
5. Physical inspections of properties by Safety Engineers and by all levels of employment to find hazardous conditions and procedures.

There are many other phases which have equal importance in our Safety Program but will not be discussed. A few of them are:

1. A Visual Aids Program, including films, film strips, safety graphs, posters, and suede boards.
2. Driver Training Program.
3. Eye Protection Program.
4. Safety Shoe Program, whereby safety shoes are made available to employees at reduced cost.
5. Safety Research activities, whereby safety personnel and key personnel in the various departments are kept advised of new developments in safety equipment and procedures and whereby technical safety material is briefed and distributed.

SAFETY MEETING PROGRAM

A goodly portion of the world's business is done through the medium of meetings of an endless variety. Meetings, then, occupy a very important position in our way of life. This, then, is the way we look upon our Safety Meetings. If they are worth holding at all, then they are worth the time and effort required to make them interesting, instructive, informative and entertaining.

Texaco has exerted a great deal of effort in that direction. That the effort has not been wasted is attested by the high attendance at the 7,000 meetings held last year on a monthly basis.

All meetings are planned a year in advance, and an even longer period of preparation goes into training those responsible for making the sessions a success. Years ago when we first started holding regularly scheduled safety meetings, about all that was furnished the safety group was the date of the meeting. It was up to someone in the group to get together material for discussion. As a consequence, there was a lack of uniformity in objectives and certainly a wide variety in the quality and value of the safety meetings.

Later, we began furnishing from our central safety office materials for use in the meeting. We still didn't have the answer. While we, in a measure, accomplished uniformity in material content of the safety meetings, we found that we were not getting it over as well as we wanted. The safety groups were not all self-sustaining. We needed leaders in the groups themselves, so a great amount of study was given the problem of training leaders.

A Safety Meeting Chairmen's Manual was developed. Next, we held training schools at which chairmen and secretaries—the key figures in safety meetings—chosen by their respective safety groups, such as geophysical crews—were taught how to plan meetings effectively and conduct them properly. Fundamentals of public speaking were taught; and as the chairmen were familiarized with their assignments they made great gains in poise and the ability to "think on their feet." These Safety Chairmen Training Schools are now held annually.

To facilitate control of the meetings, the chairmen are given a time schedule which enables them to plan each phase of the meetings so it will not encroach on the time allotted to another topic. Also helpful are reminder cards which give chairmen some timely hints regarding the meetings. Minutes of all sessions are kept by a standardized procedure on a prescribed form and then sent to plant, division and departmental management as well as to the central safety office.

To assist the chairmen in planning their sessions, the Houston office prepares a Safety Subject of the Month and a Safety Suggestion Bulletin. Chairmen receive this material six weeks in advance and use it as a nucleus in planning their meetings. The safety subjects are prepared a year in advance with considerable attention to the selection of titles which will stimulate attendance.

Material in the Safety Suggestion Bulletin covers short range approaches to accident prevention problems. These are problems which from statistical research appear to be those causing the majority of personal injuries or automotive accidents. Also included is a safety or inspirational poem, a short

driver training paragraph, an off-the-job safety item, and such additional material as space permits. With the vast amount of material available, each safety chairman, or his program committee, can use or adapt those portions which will be of most value to the local group.

FIRST AID TRAINING

An outstanding factor in the Company's Safety Program is first aid training, now in its 20th year at Texaco. Three years ago, as chairman of the American Petroleum Institute First Aid Committee, the writer was asked to look into the development of a first aid and safety training course beamed specifically for use in the petroleum industry. The result was the A.P.I. First Aid Flip Chart developed for A.P.I. instructors, using as a base The Texas Company's experience in First Aid Training. These materials are now also used by The Texas Company. Each page in the flip chart is divided into two parts. One side—the student's side—contains graphic illustrations of the particular lesson being discussed. The other side—the instructor's side—contains an instruction outline regarding the material and illustrations on the student's side. In addition, the student takes home with him a first aid reminder and refresher in the form of a booklet which is a miniature of the flip chart.

Likewise helpful is the Texaco First Aid Instructor's Training Manual, used as a supplemental guide by the instructor in training employees. This manual contains information on methods of instruction, training materials required and where to obtain them, and the administrative details necessary in keeping proper records. The manual also offers supplemental background information and statistics for the instructor.

Much emphasis is placed on the annual First Aid Instructors' Schools, of which 14 were held this year at locations from coast to coast, including one in Canada. Instructors return to these schools each year for the two-day training and refresher course. Cards are given at the conclusion of each school to both the instructors and the students. Each geophysical party sends a First Aid Instructor annually to the nearest school for training or retraining. Instructors who have participated in the program for 20 years receive gold cards; those who have served 15 years or more, but less than 20 years, receive silver cards; while others with fewer years of instruction to their credit receive cards identified by a variation in the color of engraving.

In addition to American Petroleum Institute First Aid Training Cards, each year individual Texaco First Aid Training Cards are issued, indicating the cumulative training of each employee.

First Aid training has had a definite bearing on the reduction in accidental injuries. Since 1938, the company has maintained the chart shown in Figure 1, which definitely indicates that in those years when first aid training was high, the injury frequency rate was low; and when training was low, the injury frequency rate was high. This did not hold true in 1944, 1946, 1947 and 1948, but there were definite reasons. In 1944 the war had an impact upon the program; in the latter years men returned to jobs in which they were out of practice; then there was a program of job safety training which did not include our entire First Aid Course, in which instance no First Aid Training awards were issued; and finally there was a tremendous expansion program, as well as other influencing factors too numerous to mention.

In 1951 the First Aid Training Program was intensified at certain strategic points and was held in conjunction with an educational project on Protection Against Atomic Attack. As a result, the number of employees trained in First Aid in 1951 was greater than the trend. It is noted, however, that figures for 1952 reflect the steady upward trend, starting from 1943; while the injury frequency rate trend has moved downward, reflecting the aforementioned inverse ratio.

TEXACO SAFETY DIGEST

The *Texaco Safety Digest* is an invaluable instrument in the development of safety consciousness and the promotion of favorable industrial and public relations. In the last ten years, hundreds of articles written specifically for our *Safety Digest* have been reproduced in other company publications across the nation. An internal-external publication with a circulation exceeding 17,000, the *Digest* contains, among other features, feature articles and editorials on safety, news items and sta-

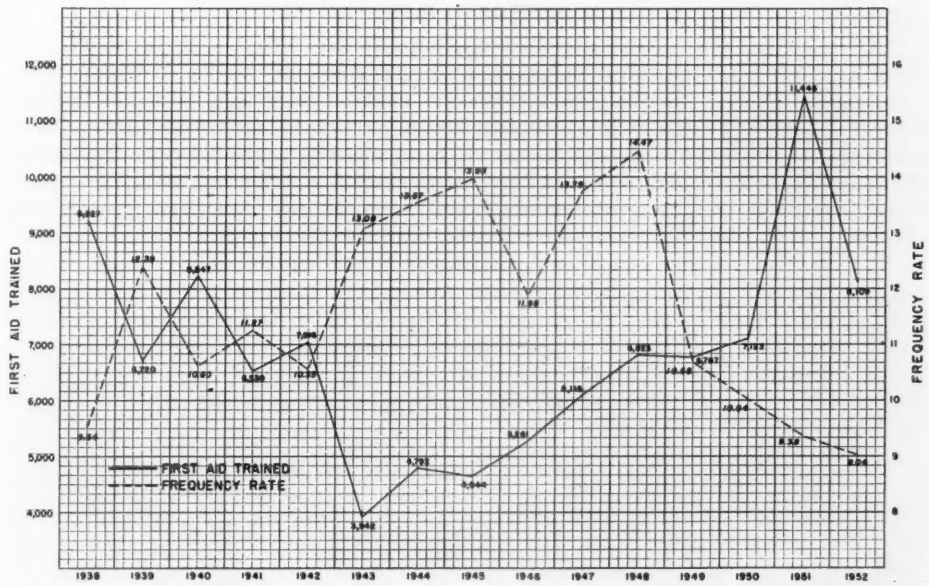


FIG. 1. Chart showing relation between first aid training and accident frequency rate for The Texas Company

tistics on the progress of our Safety Program, and our Texaco Safety Honor Roll. The Honor Roll is a list of those who have received the Texaco Life Saving Award—a gold watch awarded to employees who save the life of another person at the risk of their own. Also included are the names of the employees who have won the National Safety Council President's Medal, given when a life is saved by artificial respiration, and the names of employees who have received the National Safety Council Certificate of Assistance for aiding in cases where the President's Medal is awarded.

At this writing, 36 employees have received or have been approved for receipt of the Texaco Life Saving Award and one non-employee has received this award for having saved an employee's life. In addition, two Texaco Life Saving Awards are being processed for approval. Seventy-eight employees (two of whom were from the Geophysical Division of our Producing Department) have now received the National Safety Council President's Medal, and one is pending. Twenty-one employees have received the National Safety Council Certificate of Assistance and two are pending. This represents a tremendous saving of lives and speaks well for the quality of our First Aid Training.

OTHER MANUALS

Several manuals in addition to the First Aid Instructor's Manual and the Safety Meeting Chairmen's Manual are used to secure greater cooperation in field operations. Of importance is the Classification of Personal Injuries Manual, which contains rules and regulations governing the interpretation and coding of personal injuries.

Personal injuries are classified under five headings: Part of Body Injured, Nature of Injury, Type of Accident, Source of Injury, and Cause of Injury. Statistical information developed under each of these headings directs the safety organization toward specific points of attack in reducing accidents.

Another important link with the field forces is the Rules Governing Safety Awards Manual. Since the company has an extensive award program involving many different types of incentive awards, it is imperative that men in the field be acquainted with the rules governing these awards and the procedures for securing them.

SAFETY AWARD DINNERS

Our Producing Department has in effect what is known as a Safety Award Dinner Program, whereby employees and their wives are honored at Company expense. (See Fig. 2) When a Safety Group operates for five years or 250,000 man-hours—whichever comes first—without a disabling injury, it becomes eligible for its first award banquet, picnic or barbecue. When that record is extended by two years or 100,000 man-hours—whichever comes first—the Safety Group becomes eligible for succeeding banquets or picnics. Last year 37 Safety Award Dinners were held in our Producing Department. Of these, 6 were for geophysical parties and were attended by representatives of Geophysical Division management, the Safety Division, and other key personnel.

FIG. 2. Safety Award Dinner, Seismic Party No. 25, Crosby, North Dakota, December 5, 1952.

It is conceded by all concerned that this program also has had a great effect upon the establishment of favorable industrial and public relations.

SAFE DRIVING AWARDS

In late 1935 the company began the practice of granting Safe Driving Award Cards and Pins. A driver must operate a car one year without an accident to obtain a card and pin. Each year he extends his safe driving record he is given a card and pin indicating his period of safe driving. The company now has employees who are wearing 17-year pins. Some of these employees have safe driving records extending in excess of 17 years, but no awards cover periods prior to the award inauguration date.

OTHER AWARDS

The highest company award for which the various departments compete is the President's Award. (Fig. 3) Competition is based on improvement in the disability frequency rate, and when one of the major departments wins this trophy for three consecutive years, it retains permanent possession.

Divisions within each Department in turn compete for a Departmental Award. Within our Producing Department, the Geophysical Division won the departmental award for 1952 by virtue of having a frequency rate of 1.16 disabling injuries per million man-hours. In fact, there was only one disabling injury in the Geophysical Division in 1952. In other words, 23 out of 24 geophysical parties in the United States worked the entire year without sustaining a disability. It is of further interest to note that we have one seismic party which has operated continuously in the Permian Basin since October 15, 1939 without a disabling injury.

THE ULTIMATE GOAL

As can be seen from this brief discussion of the handling of a complex safety program in an integrated oil company, we try to approach the problems from all angles and at all levels of management and work force. Although no mention has been made of inspections for the determination of physical hazards, the company does not overlook the benefits of engineering inspections. The country is zoned, and safety engineers make inspections in their zones as often as their travels and other duties permit. In addition, the operating departments in many locations have safety inspectors. However, primary emphasis in our safety program is on safety training—in finding means of reducing human failure and in creating safety consciousness in all levels of employment. In this manner, the necessity for physical inspections by professional safety engineers is reduced. Every employee is on the lookout for unsafe conditions and unsafe practices and thereby becomes a safety engineer.

COMPENSATION RATES

These physical inspections and the broad educational aspects of our Safety Program have combined to produce favorable credits in our compensation insurance rates in the majority of states throughout the country.

Injury frequency rates are not a true criterion. We must face up to the question, "As far as compensation insurance rates are concerned, are we operating in the 'black' or the 'red'?" This, then, is the yardstick—and the only genuine yardstick—by which the success of a Safety Program can be measured.

CONCLUSION

Yes, we raised our children on dynamite, gasoline and water; but we all go down the road of life together, with the same desires for the good things in life—opportunities for our children and security for our old age. Therefore, we all have much in common and we must "do unto others as we would have them do unto us." We must let our sincere attitudes of safety shine so bright that others might find their way to that avenue of individual responsibility, freedom from personal injuries, happiness, longevity of life, and service to our fellow man and God Almighty.

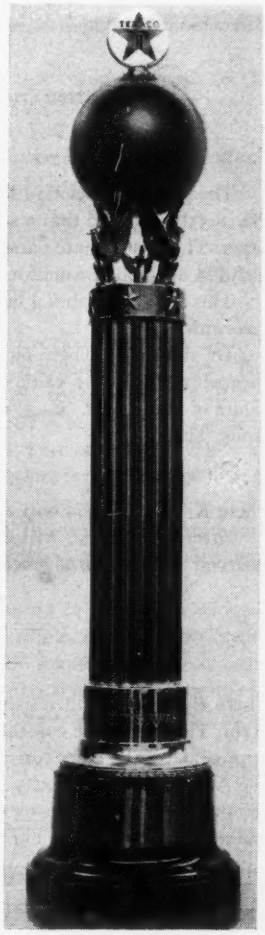


FIG. 3. **The President's** Award.

DISCUSSION AND COMMUNICATIONS

LETTERS TO THE EDITOR

UTILIZATION OF S.P. DATA IN EVALUATING VELOCITY FUNCTIONS

July 8, 1953

To the Editor of *Geophysics:*

The paper "A Velocity Function Including Lithologic Variation" (*Geophysics*, Vol. 18, pp. 271–288, 1953) suggested that a specific velocity function should be of the form of Equation (11) of that paper. The penultimate paragraph mentioned that a suggestion offered by Dr. L. de Witte might be useful in evaluating equation (11).

This letter describes a first attempt at such an evaluation and the encouraging results obtained therewith.

Dr. de Witte pointed out that by utilizing S.P. data for a particular sand in a single field a fair approximation to the value of water resistivity R_w can be obtained by assuming that the greatest values of static *S. P.* (E_{max}) at a given value of mud filtrate resistivity, R_{mf}, correspond to clay-free sands. Then

$$E_{max} = K_t \log (R_{mf}/R_w)$$

where K_t is a function only of temperature for a clay-free sand.

After consultation with Dr. de Witte, it was decided to extend the assumption to include any reservoir rock within a generally conformable section. The following equations were then set up:

$$V = 1535\ (\Phi Z)^{1/6} \tag{11a}$$

$$\Phi = R_t/0.25(4R_w')^{E/E\max} \tag{11b}$$

$$E_{max} = 70 \log (R_m'/R_w') \tag{11c}$$

where R_m' is the mud resistivity corrected to 100° F. and R_w' the water resistivity determined by (11c). The use of the constant 70 and mud resistivity corrected to a constant temperature roughly approximates the more correct equation of de Witte.

As a result of a velocity log in a well in Texas called to the writer's attention by R. A. Broding, the definition of Φ given by (11b) was indicated. E is the mean value of the S.P. over the interval where R_t is determined. For a clay-free sand equation (11b) reduces to

$$\Phi = R_t/R_w = F \quad \text{when} \quad E = E_{max}$$

and

$$\Phi = 4R_t \quad \text{when} \quad E = 0.$$

This latter assumption is undoubtedly an over-simplification. The constant of (11a) is related to the constant 1948 by the sixth root of 4.

The constants of these equations, derived from a velocity survey in Texas, were checked by two surveys in Oklahoma. The equations were next applied to the S.P. curves of the forty-six Alberta wells shown in Figure 6 of the cited paper. The corrections derived in this manner were in close agreement with the contours of Figure 6 and when the formulas (11a, b, c) were applied to the data of Figure 5, the maximum deviations from the measured times ranged from +.023 to −.016 seconds with a mean deviation of .008 seconds, compared to +.020 to −.018 seconds and .0079 seconds for the data of Figure 7.

About thirty surveys from other areas have been tested by these formulas with deviations of about the same order of magnitude. The largest deviation found to date is .030 seconds. However some S.P. curves, notably where $R_m = R_w$, have defied analysis. While such data may serve later as a clue to the modification of (11b), it seems probable that a better approach would be the determination of a formula for formation factor in shale either from theory or from more direct experimental data.

The approximation of (11c) is warranted only as a comparatively simple calculation to test the

general validity of the method. When a better form for equation (11b) is found, the more nearly correct formula for determining R_w should be applied.

The account of this investigation is given as evidence that even this crude approach to the problem suggests the usefulness of the S.P. curve in the final solution.

L. Y. FAUST
Amerada Petroleum Co.
Tulsa, Okla.

RADIO PROPAGATION EXPERIMENTS IN CARLSBAD CAVERNS

June 10, 1953

To the Editor of *Geophysics:*

The Research Laboratory of United Gas Corporation, Shreveport, Louisiana, recently investigated some features of radio propagation through the earth at Carlsbad Caverns, New Mexico. The output of two transmitters operating at 1616 and 1700 kc with outputs less than 0.1 and 7 watts respectively were coupled into the earth and the field strength was measured in an unwired passage of the Caverns which lay 700–750 ft. below the surface. Six surface positions were occupied; seven to 25 readings were made on each run over the 2,500 feet of passage used, giving data for actual transmission distances through the earth of 700 to 3,000 feet.

The maximum distance at which signal was detected was 3,000 feet; this was not the maximum distance which could have been reached on this run. Two-way communication was established over distances of 1,400 feet with good efficiency.

The data obtained are still being analyzed. The results to date are not in agreement with all features of similar experiments conducted in recent years but are highly credible. Further experiments are being planned to extend the range of the data both as to distance and frequency and to investigate certain highly interesting results, in particular the extent of the induction field and the value of the attenuation. It is expected that a full account of all this work will be submitted for publication as soon as the experiments are completed and the data analyzed.

This letter is submitted for possible inclusion under Discussions and Communications in *Geophysics.*

FIELDING M. MCGEHEE, JR.
Research Department
United Gas Corporation
Shreveport, Louisiana

ELECTROMAGNETIC COUPLING BETWEEN A CIRCULAR LOOP AND A CONDUCTING SPHERE

May 20, 1953

To the Editor of *Geophysics:*

It is the purpose of this note to derive an expression for the change of self-impedance of a circular wire loop due to the presence of a coaxially located conducting sphere. The result has application to inductive type measurements of conductivity and permeability of diamond drill core samples (see Ward, 1953).

A sphere of radius a with electrical conductivity σ_1 and permeability μ_1 is situated at the centre of a spherical coordinate system (r, θ, ϕ). The insulating exterior medium air has a permeability μ_2. A wire loop carrying a current I amperes with angular frequency ω is situated at $\theta=\beta$ and $r=b$. The primary vector potential, in the absence of the sphere, has only a ϕ component and is given by Smythe (1950):

$$A_\phi{}^p = \frac{\mu_2 I \sin\beta}{2} \sum_{n=1}^{\infty} \frac{1}{n(n+1)} \left(\frac{r}{b}\right)^n P_n{}^1(\cos\theta) P_n{}^1(\cos\beta).$$

The resultant vector potential A_ϕ due to the presence of the sphere can be obtained in an identical

manner to that of a previous analysis by Wait (1953) so without repeating any of the details, it follows that

$$A_\phi = A_\phi^p + A_\phi^s$$

with

$$A_\phi^s = -\frac{\mu_2 I \sin\beta}{2} \sum^{\infty} \frac{a^{2n+1}}{b^n r^{n+1}} \frac{R_n}{n(n+1)} P_n^1(\cos\theta) P_n^1(\cos\beta)$$

where

$$R_n = 3(M_n + iN_n).$$

The functions M_n and N_n are the "in phase" and "quadrature" components of the induced multipoles in the sphere. They involve the parameters $(\sigma_1\mu_1\omega)^{1/2}a$ and μ_1/μ_2 and have been discussed numerically on previous occasions (Ward, 1953; Wait, 1953).

The change of self impedance of the wire loop due to the presence of the sphere is then given by

$$\Delta Z = \Delta R + i\omega\Delta L = -i\omega A_\phi^s 2\pi b/I$$

for $\theta=\beta$.

When the wire loop is in the equatorial plane (i.e. $\beta=\theta=90°$) of the sphere, its radius is then equal to b and it follows that

$$\Delta L = -3\mu_2\pi a \sum_{1.3.5.}^{\infty} \left(\frac{a}{b}\right)^{2n} \frac{M_n(n+1)}{n} \left[\frac{1\cdot 3\cdot 5\cdot \cdots \cdot n}{2\cdot 4\cdot 6\cdot \cdots \cdot n+1}\right]^2$$

and

$$\Delta R = 3\mu_2\pi a\omega \sum_{1.3.5.}^{\infty} \left(\frac{a}{b}\right)^{2n} \frac{N_n(n+1)}{n} \left[\frac{1\cdot 3\cdot 5\cdot \cdots \cdot n}{2\cdot 4\cdot 6\cdot \cdots \cdot n+1}\right]^2$$

where the summations are over odd values of n only.

It readily follows from these results that if $(a/b)^4$ is much less than one, only the first term need be considered. This result then takes the simple form

$$\Delta L = -KM_1$$

and

$$\Delta R = \omega K N_1$$

which agrees with Ward's equation (17) and (18) where K is a constant independent of frequency.

It is pointed that the simple form of this result can only be used if the diameter of the loop (or solenoid) is not comparable to the diameter of the specimen.

I wish to quote the following excerpt from a letter which Dr. Ward has written me concerning the above derivation: "Your analysis of the sphere in coil problem is certainly more elegantly presented than mine and brings out clearly the restriction that $(a/b)^4$ must be $\ll 1$. I would appreciate it if you would publish this as a letter to the editor in *Geophysics*. The assumption of a uniform field over the sphere amounts to the same thing as the above restriction, but I did not point this out clearly."

REFERENCES

Smythe, W. R. (1950) *Static and Dynamic Electricity*, 2nd Ed. p. 274. McGraw-Hill Book Co., New York.

Wait, J. R. (1953) A conducting permeable sphere in the presence of a coil carrying an oscillating current, *Can. Jour. Phys.*, Vol. 31, p. 670.

Ward, S. H. (1953) Electrical conductivity of diamond drill core specimens, *Geophysics*, Vol. 23, p. 434.

JAMES R. WAIT
Radio Physics Laboratory
Defence Research Board
Ottawa, Canada

ERRATA LIST FOR PAPERS IN *GEOPHYSICS* BY JAMES R. WAIT

June 2, 1953

To the Editor of *Geophysics:*

I am herewith sending a list of typographical errors and omissions of several of my papers in *Geophysics:*

"Transient Electromagnetic Propagation in a Conducting Medium" Vol. 16, pp. 213–222, 1951.

p. 215. In equation (20), $2(\alpha/2t^{1/2})$ should be replaced by $2(\alpha/2t^{1/2})^3$,

p. 220: In equation (32), the factor $\mu/4\pi t(1/\pi)^{1/2}$ should be replaced by $(\mu/8\pi t)$,

p. 221: equation (34) should read

$$E_z(t) = \mu/4\pi t \exp(-\beta^2\rho^2).$$

"A Conducting Sphere in a Time Varying Magnetic Field" Vol. 16, pp. 666–672, 1951.

p. 668: The defining equation for α should read

$$\alpha = (i\sigma_1\mu_1\omega - \epsilon_1\mu_1\omega^2)^{1/2}R$$

p. 667: (at bottom of page), the factors $(\alpha z/2)$ and $(2z/\alpha)$ should be replaced by $(\pi z/2)$ and $(2z/\pi)$ respectively.

"A Note on Dipole Radiation in a Conducting Medium," Vol. 17, pp. 978–979, 1952.

p. 978: The denominator in the expressions for the ϕ components of the fields should be $4\pi r^2$ rather than as shown.

"Transient Coupling in Grounded Circuits," Vol. 18, pp. 138–141, 1953.

p. 139: The expression $4(\beta n)$ should read $\psi(\beta x)$.

p. 141: The expressions $4(\beta l)$ and $4(2\beta l)$ in equation (7) should read $\psi(\beta l)$ and $\psi(2\beta l)$ respectively.

JAMES R. WAIT
Radio Physics Laboratory
Defence Research Board
Ottawa, Ontario

MEMORIAL

EARLE WINSTON JOHNSON (1902–1953)

This memorial is in tribute to a very dear friend.

Earle Winston Johnson died very suddenly Tuesday, August 11, 1953, at 7:00 P.M., while on a business trip to Jasper, Alberta, Canada. Earle's untimely passing was a great shock and loss to his immediate family and widespread group of friends.

Earle was born October 3, 1902, at Denison, Texas, and after attending Texas A. & M. College and the University of Texas, entered geophysical work for the Roxana Petroleum Corporation. He later joined Geophysical Service Incorporated and then helped Henry Salvatori organize Western Geophysical Company before organizing General Geophysical Company in 1935. Earle was President of General, and his untiring efforts resulted in its growth to one of the leading geophysical companies in the world. He was ardently proud of General Geophysical Company.

During World War II, Earle contributed very substantially to the war effort in helping to develop the proximity fuse, as evidenced by the following telegram from Dr. Merle Tuve, Director of Applied Physics Laboratory, Johns Hopkins University:

"Many thanks to Sappington for wire. Please tell Virginia Johnson we quietly share her grief. It never seems possible to say enough to each other but the heart speaks and another hears. Without Earle Johnson's help and courageous acts in the early days of the war our work in Section T could not have been finished in time to stop the battle of the buzz bombs against London. Many Americans and British men and women owe him an unknown debt of gratitude. I grieve to say farewell. We loved him. Merle Tuve"

Earle's interests were manifold and he contributed generously of his talents and untiring efforts to many friends and organizations alike. He was a past President of the Houston Section of the Society of Exploration Geophysicists, a member of the Houston Geological Society, American Association of Petroleum Geologists, Society of Exploration Geophysicists, Petroleum Club, Houston Club, Brae-Burn Country Club and the Chambers County Hunting Club. He was a lover of birddogs and spent many hours in the field behind his fine dogs, as well as in the duck blinds, regardless of weather. His many hunting companions will miss him immeasurably.

Earle married Virginia McClain on February 4, 1935, at Alma, Nebraska. He was a very devoted husband and is survived by his widow, whom he fondly called "Kewpie," his mother, Mrs. Howell A. Johnson, an aunt, Mrs. Emma Holt, and an uncle, Mr. Grover C. Johnson, all of Houston.

Earle Johnson will always be remembered by his multitude of friends and business associates for his warmhearted friendship, his forthright, honest business manner, and as one whom it was a privilege to know.

ROY L. LAY

Houston, Texas
September 16, 1953

MEMORIAL

NORMAN J. HIGHFIELD (1914–1953)

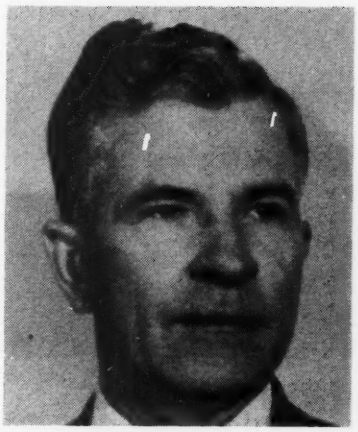
Norman J. Highfield, party chief and Seismologist for Marine Exploration Company, died on the 8th of February, 1953 of a heart attack that followed a short illness. He died a few hours after arriving at his home in Henderson, Texas. He was located at New Orleans, Louisiana, where he had been working on an offshore seismic crew. Mr. Highfield's untimely death at an early age of 39 was a severe blow keenly felt by his many friends and associates, and of course, an enormous loss to his family.

Norman was born May 21, 1914 at Topeka, Kansas, to Mr. J. W. Highfield and Zella P. Highfield. He attended school in El Paso, and received his formal education at Texas Western with a B.S. Degree in Mining. His 11 years of geophysical work which took him from Arkansas to Louisiana on to West Texas and as far as New Mexico began with five years on a seismograph crew for National Geophysical Company followed by five years with Lee Geophysical Company and almost a year with Marine Exploration Company of Houston, Texas.

He is survived by his wife, Josephine Highfield, and his six year old son, Norman, of Henderson, Texas.

SAM M. PENA

CONTRIBUTORS

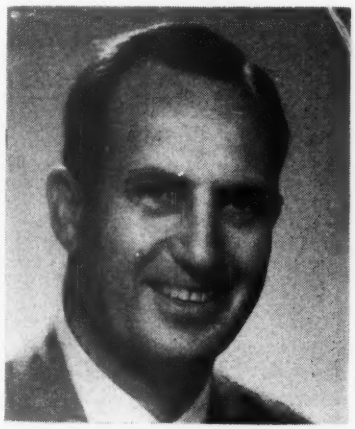


GLENN M. CONKLIN

GLENN M. CONKLIN received his B.A. degree in physics from the University of Texas in 1933. He worked for Humble Oil and Refining Co., Heiland Research Corp., and Seismograph Service Corp. in various positions on seismograph crews until 1945.

In 1945 he joined the Sun Oil Company as research computer and is now section head in charge of the Dallas division of the seismograph department.

He is a member of Society of Exploration Geophysicists, Dallas Geological Society, and Dallas Geophysical Society.



JOHN DALY

JOHN DALY received his degrees of B.S. in science and M.S. in geology and paleontology from the California Institute of Technology. After two years as a geologist with International Geophysics, Incorporated, he was employed by Shell Oil Company in California for nine years as seismologist and geologist.

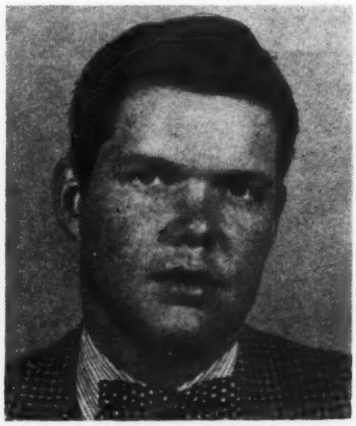
In 1942 he joined Honolulu Oil Corporation and shortly thereafter moved to West Texas. In 1950 he served as division supervisor for General Geophysical Company in West Texas and New Mexico. He has been in charge of seismograph work in California, West Texas, New Mexico, Colorado, Wyoming and Mississippi. Since November, 1951 he has had his own office at Midland, for consulting in geophysics and geology.

He is a member of the Society of Exploration Geophysicsts, The American Association of Petroleum Geologists, American Geophysical Union, and Society of Economic Geologists and he is a Fellow of the Geological Society of America.

CHARLES A. MILLER

CHARLES A. MILLER completed one year of high school before enlisting in the U. S. Marine Corps in 1910, and in 1913 he transferred to the U. S. Naval Medical Corps, later becoming an officer. He first started in safety work in 1914 at Worcester, Mass., with the Worcester Pressed Steel Company and later served as safety engineer and safety director for several insurance companies and industrial organizations. He was employed as safety engineer at The Texas Company's Port Arthur works for several months in 1922 and returned to the company in 1934 as supervisor of safety. At present he is in charge of safety for The Texas Company, its domestic subsidiaries and affiliates.

Since 1934 Mr. Miller has held positions of leadership in several safety organizations. He is presently on the executive committee of the Petroleum Section, National Safety Council, and as a member of the American Petroleum Institute he is serving as chairman of the First Aid Committee and member of the Planning Committee, Committee on Safety in Drilling and Production Operations, and Committee on Awards.



CHARLES B. OFFICER, JR.

CHARLES B. OFFICER, JR. received the degrees of Sc.B. in physics from Brown University in 1947, M.A. in physics from Wesleyan University in 1948, M.S. in physics from Yale University in 1949, and in 1952 the Ph.D. in geophysics from Columbia University.

From 1947 to 1948 he held a teaching fellowship at Wesleyan University. From 1948 to 1949 he was instructor in physics at Yale University. From 1949 to 1951, as research associate in geophysics at Lamont Geological Observatory of Columbia University, he was primarily engaged in geophysical exploration of the continental margins. From 1951 to 1953 he has held the position of geophysicist at Woods Hole Oceanographic Institution, engaged in research on various problems dealing with underwater sound transmission, ambient noise, and channel propagation, under contract with the U. S. Navy. Currently, for the year 1953–1954, he is a Fulbright Fellow in geophysics in New Zealand.

Dr. Officer is a member of the Society of Exploration Geophysicists, American Geophysical Union, Seismological Society of America, Geological Society of America, and American Physical Society.

OTTO ROSENBACH received the *Staatsexamen* in 1939 in mathematics and physics at Koenigsberg University. From 1940 to 1945 he was geophysicist with Prakla Gesellschaft für Praktische Lagerstaettenforschung GmbH, holding the position of party chief from 1941 to 1945 for that company. In 1947 he received the degree of Dr.-Ing. in geophysics at Bonn University, and in 1951 received the degree of Dr.-Ing Habil., qualifying as a recognized university teacher. In addition to his teaching duties at Bonn University, Dr. Rosenbach serves as adviser to Prakla, Hannover.

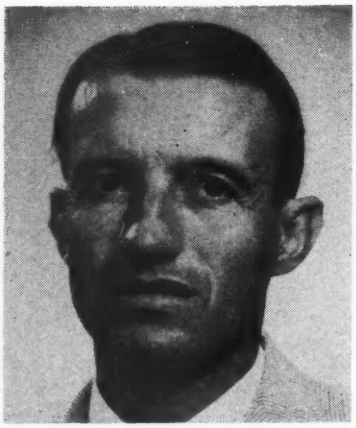
He is a member of the German Geophysical Society, European Association of Exploration Geophysicsts, and the (German) Society of Applied Mathematics and Mechanics.

OTTO ROSENBACH

OSCAR SCHNEIDER-RIQUELME

OSCAR SCHNEIDER-RIQUELME graduated from the Universidad de Chile in 1941 with degrees in both civil and electrical engineering. He was an electrical engineer for the Empresa Nacional de Electricidad (1941–1949). From 1944 to 1949 he also taught electrical engineering at the Escuela de Artes y Officios. Since 1949 he has been a geophysicist for Empresa Nacional del Petróleo. From 1951 to 1953 he did graduate work in geophysics at the California Institute of Technology. He is now chief geophysicist for Empresa Nacional del Petróleo at Punta Arenas, Chile.

Mr. Schneider-Riquelme is a member of the Instituto de Ingenieros de Chile, Society of Exploration Geophysicists and Sigma Xi (associate).

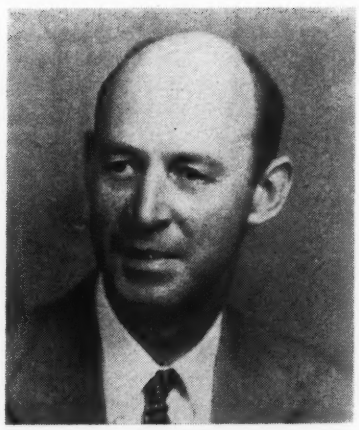


FRANCIS A. VAN MELLE

FRANCIS A. VAN MELLE was born in Amsterdam, the Netherlands, in 1903, and received the degree of Ph.D. from the University of Groningen in 1928 on a thesis in X-ray crystallography. Immediately afterward he entered the service of the B.P.M., technical subsidiary of the Royal Dutch Oil Company, as gravity party chief and later seismologist in Indonesia and Mexico. He came to this country as an immigrant in 1937 and the next year entered the service of the Shell Oil Company, as seismologist in charge of an experimental crew. Since 1943, he has been research seismologist in the Shell Exploration and Production Laboratory in Houston, which recently became the Exploration and Production Research Division of Shell Development Company.

K. R. WEATHERBURN, was born in Melbourne, Australia, January 2, 1914. He attended the University of Western Australia, 1932–34 and 1936, receiving the B.Sc. degree in physics. In 1935 he was employed on a geological survey for Freney Kimberley Oil Company in northern Australia. He entered services of a subsidiary of Royal Dutch Shell in 1937 as gravity observer in Papua, New Guinea. From August 1938 to December 1939, he trained in gravity and seismology with B.P.M., The Hague, and Shell Oil Company, Houston, Texas. He was gravity party chief in Java, Indonesia and Queensland, Australia from 1940 to 1942; from 1943 to 1951, seismologist at Shell's E. and P. Research Laboratory, Houston, Texas, and since 1951, review seismologist, Shell Oil Company, Tulsa, Oklahoma.

Mr. Weatherburn is a member of the Society of Exploration Geophysicists.



K. R. WEATHERBURN

SOCIETY ROUND TABLE

COMMITTEES

Executive Committee, Year Ending in April, 1954

President: Roy L. Lay, The Texas Company, Houston, Texas
Vice-President: Karl Dyk, Stanolind Oil & Gas Co., Tulsa, Oklahoma.
Secretary-Treasurer: Bart W. Sorge, United Geophysical Co., Inc., Pasadena, California
Editor: Milton B. Dobrin, Magnolia Petroleum Co., Dallas, Texas
Past President: Curtis H. Johnson, Geophysical Service Inc., Dallas, Texas

Standing Committee on Nominations

Chairman: Roy L. Lay, The Texas Co., Houston, Texas

Curtis H. Johnson — Sigmund Hammer

Standing Committee on Program and Arrangements

Chairman: Karl Dyk, Stanolind Oil & Gas Co., Tulsa, Oklahoma

Richard Brewer	R. W. Dudley	Harold C. Bemis
L. F. Fischer	Arnold Bleyburg	Fred Forward
H. M. Houghton	E. V. McCollum	W. L. Homan
D. R. Dobyns	Reese H. Tucker	R. N. Harding
J. P. Woods	R. G. Piety	G. A. Berg
P. A. Weirich	Milton Born	O. B. Manes
Perry Byerly	R. W. Gemmer	P. E. Narvarte
L. Y. Faust	V. J. Blum	H. O. Seigel
W. Baillie	R. B. Ross	Frank Press
A. van Weelden		E. H. Shannon

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M. King Hubbert	Perry Byerly	Sherwin F. Kelly
Beno Gutenberg		H. W. Straley III

Standing Committee on Distinguished Lectures

Chairman: Paul L. Lyons ('54), Anchor Petroleum Co., Tulsa, Oklahoma

Carl Savit ('55) — Francis F. Campbell ('57)
Peter Dehlinger ('56) — John Ferguson ('58)

Standing Committee on Radio Facilities

Chairman: R. D. Wyckoff, Gulf Research & Development Co., Pittsburgh, Pa.
Vice-Chairman: W. M. Rust, Jr., Humble Oil & Refining Co., Houston, Texas

Bart W. Sorge	C. B. Bazzoni	Daniel Silverman
E. M. Shook	V. Robert Kerr	Richard Brewer
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DIRECTORS OF THE AMERICAN GEOLOGICAL INSTITUTE

GEORGE E. WAGONER (Nov., 1954) — ANDREW GILMOUR (Nov., 1953)

REPRESENTATIVE ON DIVISION OF GEOLOGY AND GEOGRAPHY
NATIONAL RESEARCH COUNCIL

L. L. NETTLETON, Gravity Meter Exploration Co., Houston, Texas
(June, 1954)

NOMINEES FOR 1954–55 EXECUTIVE COMMITTEE

The following brief biographical sketches are presented to acquaint members of the society with nominees appearing on the official ballot which will be mailed to all Active Members in good standing in December. Bylaws Article VII, section 4, provides that "Prior to December 1, nominations in writing, signed by at least twenty Honorary Members or Active Members in good standing and accompanied by the written consent of the candidate, may be submitted to the President."

FOR PRESIDENT

PAUL L. LYONS received the A.B. degree in geology from DePauw University in 1933 and completed work on the M.Sc. in geology from The University of Tulsa in 1942. In 1934 he began work in geophysics on a Humble Oil and Refining Company seismograph party. In 1935 he was transferred to The Carter Oil Company in Tulsa as a computer. In 1943 he became chief computer and in 1947 technical geophysical supervisor for Carter. In 1949 he became technical assistant to the vice-president in charge of exploration. In 1950 he was staff geologist in Tulsa for Carter's eastern division. Since 1951 Mr. Lyons has been exploration manager for Anchor Petroleum Company, Tulsa.

PAUL L. LYONS

JOHN H. WILSON

In 1948 he served as vice-chairman of the S.E.G. Public Relations Committee, and in 1949 and 1950 as chairman of that committee. In 1950 he was also vice-chairman of the Standing Committee on Program and Arrangements. He was vice-president of the Geophysical Society of Tulsa for the 1950–1951 term. He was elected Editor of the Society, serving from March, 1951 through March, 1953, and was elected president of the Geophysical Society of Tulsa for one year beginning in May, 1952. He is at present chairman of the Standing Committee on Distinguished Lectures and member of the Special Committee on Business Office Survey, and editor of *Geophysical Case Histories, Vol. II.*

Mr. Lyons is a member of The American Association of Petroleum Geologists, Tulsa Geological Society, Geophysical Society of Tulsa, and the Society of Exploration Geophysicists.

JOHN H. WILSON received the degree of Engineer of Mines in 1923, specializing in geology, from Colorado School of Mines. Also in 1923 he started work for the Midwest Refining Co., Denver, Colorado. In 1924 he organized the company's subsurface laboratory and took charge of core-drilling. In 1925 he began geophysical investigations for Midwest. In 1926 he transferred to the Huasteca Petroleum Co., Tampico, Tamps., Mexico in charge of geophysical work and core-drilling, and in 1927 became acting geologist in charge of all geological and petroleum engineering work for that company. In 1928 he returned to the United States to take the position of Assistant Professor of Geophysics at Colorado School of Mines, teaching courses in general geophysics, theory and application of the magnetometer, and theory and application of the torsion balance. In 1929 he started work as consulting geologist and geophysicist and acted as general manager of Piper Petroleum Company engaged in geological and geophysical exploration and the production of oil. From 1934 to 1937 he was president of Colorado Geophysical Corp., Denver, and from 1937 to 1950 was vice-president of Independent Exploration Company. From January 1, 1951, he has been an exploration consultant and vice-president of Piper Petroleum Company and Woodson Oil Company.

Mr. Wilson, as Secretary-Treasurer in 1937, was one of the incorporators of the Society of Exploration Geophysicists. He is a charter member of the Society, and also is a member of The American Association of Petroleum Geologists, American Institute of Mining and Metallurgical Engineers, Fort Worth Geophysical Society (President 1952–1953), Fort Worth Geological Society, and Dallas Geophysical Society.

FOR VICE-PRESIDENT

ROY F. BENNETT

RALPH B. ROSS

ROY F. BENNETT studied electrical engineering at Oklahoma A & M College, Stillwater, Oklahoma. In February, 1929 he was employed as seismic observer with Geophysical Research Corp., continuing until August, 1931 when he returned to Oklahoma A & M to complete his college work. He joined the Independent Exploration Company as seismic observer in August, 1932. While with Independent Exploration he served as seismic observer, seismic and gravity party chief, seismic review interpreter, and geophysical instrument designer. In August, 1945 he became district geophysicist for Sohio Petroleum Company, becoming division geophysicist in 1946, and chief geophysicist in 1949. He organized the geophysical department for Sohio, including gravity and seismic crews, as well as the district supervisory force. He is presently employed as chief geophysicist attached to the general manager's staff in Oklahoma City.

He is a member of the American Association of Petroleum Geologists; Houston Geological Society; Houston Section; Geophysical Society of Oklahoma City and has been a member of the Society of Exploration Geophysicists since 1935. He was secretary of the Houston section in 1948, vice-president in 1949, president in 1950 and district representative in 1951 and 1952. Mr. Bennett was chairman of the entertainment committee for the 1953 joint annual meeting at Houston.

RALPH B. ROSS received a B.S. degree in 1931 and a M.S. degree in 1933 in Geology from the University of Pittsburgh, and was a graduate assistant in the Geology Department for the two years of graduate work. Since 1933 he has been employed continuously by the Gulf Research and Development Company, from 1933 to 1942 as a seismic interpreter, from 1942 to 1946 as a seismic party chief and from 1946 to 1950 as geophysical supervisor of the Tulsa Division. Since 1946 Mr. Ross has been assistant director of the Geology Division of the Gulf Research and Development Company and supervises the geophysical and structural geology research in that Division.

As a member of the Society of Exploration Geophysicsts Mr. Ross has served since 1950 as chairman of the Eastern Regional Program Committee, in which capacity he was in charge of the Eastern Regional Meeting in Pittsburgh in 1951 and in Toronto in 1952. Currently he is in charge of plans for the forthcoming joint meeting with the American Association for the Advancement of Science.

FOR SECRETARY-TREASURER

RICHARD BREWER

HUGH M. THRALLS

RICHARD BREWER received his B.S. degree in electrical engineering from Purdue University in 1935, after which he returned to the university for graduate work in physics and mathematics.

Mr. Brewer joined the Shell Petroleum Corporation in 1936 and, during the next six years, served as assistant seismologist and seismologist in Louisiana, Texas and New Mexico. He entered the U. S. Army Signal Corps in 1942 and was assigned to radar work, first with the R.A.F. and later with the Army Air Force, during which time he obtained the rank of major.

After his discharge from the army in 1946, Mr. Brewer was employed by The Atlantic Refining Company as assistant to the district supervisor for Atlantic's Southwest Texas district. Since 1948, he has been district seismic supervisor for Atlantic in Shreveport and, from that office, he also assists in seismic work in the Tyler and Jackson districts.

He is a member of the Society of Exploration Geophysicists, The American Association of Petroleum Geologists, the Shreveport Geological Society and the Ark-La-Tex Geophysical Society (past president and district representative). Mr. Brewer was general chairman of the Sixth Annual Midwestern Meeting in November, 1952 at Fort Worth.

HUGH M. THRALLS received the B.S. degree in physics from the University of Oklahoma in 1932 and in 1934 received the M.S. in physics from that University. From 1934 to 1936 he was with Shell Oil Company, and in 1936 joined Seismograph Service Corporation as a party chief. He became a supervisor in 1939, and chief geophysicist in 1945. In 1949 he became vice-president in charge of domestic exploration and member of the board of directors of SSC.

Mr. Thralls is a member of The American Association of Petroleum Geologists, Geophysical Society of Tulsa, Tulsa Geological Society, Oklahoma City Geological Society, and American Geophysical Union. As a member of the Society of Exploration Geophysicists he has served as second vice-president and president of the Tulsa Section. He has also served on the Standing Committee on Safety of the Society.

MEMBERSHIP APPLICATIONS APPROVED FOR PUBLICATION

The Executive Committee has approved for publication the names of the following candidates for membership in the society. This publication does not constitute an election but places the names before the membership at large. If any member has information bearing on the qualifications of these nominees he should send it to the president within thirty days. Names of the references appear in parentheses after the name of each nominee.

ACTIVE

Willard Arthur Allred (R. C. Cole, G. A. Burton, O. G. Holekamp)
Claude Aynard (Leon Migaux, Jacques LeBlanc, Lucien Beaufort)
Clarence Wilbur Becker (Andrew Gilmour, J. A. Gilmore, E. D. Williams)
Kenneth Francis Bickford (Harold Mooney, R. E. McMillen)
James Morris Clinton (J. A. Adams, V. E. Prestine, Dean Walling)
Sam James Dallison (Marvin Romberg, Robert Patterson, Sam Zimerman)
Leon Lamar Dupree, Jr. (C. J. Charske, C. L. Hubbard, W. D. Mounce)
Henry L. Ehrhardt (A. B. Hamil, G. M. Mace, Sam M. Pena)
Samuel Ray Faust (P. E. Nash, O. H. Armstrong, J. C. Menefee)
Charles Wylie Foulkes (H. R. Prescott, Frank Searcy, B. G. Swan)
Raymond Henri Joseph Geneslay (Leon Migaux, Jacques LeBlanc, Lucien Beaufort)
Frederick Samuel Gillig (K. H. Kundert, J. R. Gilliland, W. H. Morgan)
Carl H. Gullick (B. G. Swan, L. E. Whitehead, H. H. Moody)
William Earl Harper (W. M. Rust, Jr., D. H. Gardner, L. R. Ording)
Corby L. Hart (B. J. Sorrells, W. J. Harkey, W. H. Amis)
James Isaac Hastings (J. T. Hartman, R. C. Hilton, O. B. Manes)
Driscoll Arthur Henkhaus (Ross Smith, Jr., C. S. Fleischmann, J. A. Smith)
James Woodrow Higgins (H. C. Bemis, S. C. Stoneham, T. P. Ellsworth)
Joseph Weldon Hill (D. P. Carlton, C. K. Fielder, W. T. Nutt)
James Milton Hinson (H. M. Houghton, W. T. Born, K. M. Lawrence)
James Davidson Hudson (Robert H. Ray, J. C. Pollard, E. W. Frowe)
James Donald Kelly (O. C. Clifford, Jr., C. H. Hightower, M. S. Hathaway)
Theodore Samuel McGehee (C. H. Hightower, E. L. DeLoach, O. C. Clifford, Jr.)
Clifford Herbert Massie (Richard A. Pohly, R. W. Mossman, A. J. Barthelmes)
Peter Noel Somerville O'Brien (A. Baber, J. McG. Bruckshaw, J. T. Wilson)
William Ross O'Brien (G. J. Long, J. K. Pawley, R. K. Carter)
Albert George Packer (A. A. Fitch, V. V. Graf, E. B. Lindsey)
William Dwight Pemberton (R. F. Bennett, W. W. Adams, L. J. Larguier)
Theodore Anatole Pezarro (G. L. Paver, J. McG. Bruckshaw, A. A. Fitch)
Andrew Luke Pierson III (D. P. Carlton, W. M. Rust, Jr., D. H. Gardner)
Robert Richard Pittman (D. H. Clewell, J. E. White, M. B. Dobrin)
M. N. Suryanarayana Rao (H. R. Joesting, H. L. Scharon, Sigmund Hammer)
Henri Richard (Leon Migaux, Jacques LeBlanc, Raymond Maillet)
David Carl Richards (D. H. Clewell, C. G. Dahm, O. C. Haycock)
George Leroy Richards (Paul V. Hodge, Sidon Harris, Earl Thomas)
Joseph Stockton Rhodes (A. E. Smith, Frank Goldstone, L. M. H. Vreugde)
Donald Dean Roose (R. F. Aldredge, A. L. Ballou, R. W. Mossman)
Cornelis Romeijn (C. Velzeboer, O. Koefoed, P. S. Stoutjesdijk)
Otto Rosenbach (E. J. Handley, D. T. Germain-Jones)
Eugene Rusconi (J. W. Thomas, Donald Rockwell, Ed Schempf)
Steward Leo Russell (A. B. Hamil, G. M. Mace, Jr., B. K. Jonson)
Charles R. Rutherford (C. H. Green, K. E. Burg, R. W. Olson)
Herman J. Schmalz (C. C. Brooks, J. J. Rupnik, W. A. Reeves)

Ritzoo Herman Theodoor Schut (A. van Weelden, B. Baars, B. deBlank)
Jerome Joe Segal (R. H. Ray, J. C. Pollard, E. W. Frowe)
Blake Manor Sellers (C. H. Carlisle, H. G. Patrick, C. S. Fleischmann)
Clemille Franklin Sellers (R. H. Ray, E. W. Frowe, J. C. Pollard)
Randolph F. Simon (H. H. Frost, M. B. Dobrin, D. H. Clewell)
Samuel Theodore Spradlin (W. L. Hershelman, Karl H. Kundert, Jack Martin)
Oscar LeVerne Taylor (J. E. Dorris, Ira L. Nash, J. A. Keeling)
Phil Howard Thomas (Joe B. Hudson, O. K. Fuller, Jr., F. E. Schultz)
James Wilson Vanderbeek (W. H. Hawkes, G. E. Ellis, W. H. Matthews)
Cecil Henry Vandegaer (O. B. McReynolds, Jr., R. A. Crain, R. D. Roberts)
Johannes van Keulen (A. van Weelden, D. R. Brown, O. Koefoed)
Francis Raymond Versaw (R. C. Kendall, H. L. Thomsen, F. Goldstone)
Kenneth R. Wells (E. W. Johnson, P. M. Konkel, G. J. Smith)
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Lawrence Henry Wigley (R. S. Epperson, R. P. Warren, H. G. Patrick)
Lucian Minor Wilkens (R. H. Ray, J. C. Pollard, E. W. Frowe)
Hans von Helms (E. J. Handley, D. T. Germain-Jones)
Waldemar Zettel (E. J. Handley, D. T. Germain-Jones)

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William George Hamer Hodges (R. H. Ray, J. C. Pollard, G. D. McElree)
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Russell Emerson Steele (Harris Cox, Carl Cain, J. E. Barthelemy, Jr.)
Ernest Stephens, Jr. (G. E. Seiler, D. E. Steel, E. W. Gilbert)
Frank Bailey Summers (J. E. McGee, W. B. Lee, J. R. Monkhouse)
E. Keith Swanson (S. G. Manos, C. O. Johnson, H. E. Wright)

Joseph Bert St. Romain (J. H. Cross)
Carlton E. Stuart (C. H. Green, Sam Zimerman, A. E. Storm)
Thomas Collin Sledge (F. J. Agnich, Robert Dyk, Earl Thomas)
Clarke Stein (R. A. Peterson, F. W. Perrin, L. K. Morris)
Boguslaw Jan Szenk (J. E. Dorris, I. L. Nash, J. A. Keeling)
Joseph Wall Tedder, Jr. (W. O. Novelly, Bill Henderson, F. B. Smth)
Daniel Alvin Taiclet (J. E. Spencer, L. C. Spencer, F. L. Travis)
Norman Eugene Taney (E. F. Zagst, H. C. Smith, J. D. Marr)
John Andrew Tessari (S. O. Patterson, E. F. K. Zarudzki, T. J. Mouche)
Howard Francis Thompson (A. E. McKay, C. H. Hightower, B. G. Hubner)
Dee LeRoy Tipton (Don C. Short, Tobe Lister, Maynard Harding)
Kenneth Ray Tubbs (M. C. Kelsey, E. F. McMullin, J. F. Rollins)
Lewis Kelley Turner (B. G. Swan, L. E. Whitehead, Charlton Kerr)
Edward Vetter (C. H. Green, F. J. Agnich, K. E. Burg)
Gonzales Van Not (D. R. Brown, B. Baars, Victor Ulrich)
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Max E. Wimber (Richard Williams, C. B. Smith, V. H. Waddell)
James Laverne Waggoner (E. J. Handley, V. H. Waddell, K. H. Waters)
Ray Franklin Weston (Ray St. Germain, E. P. Evans, E. E. Jones)
Bradley Fredric Williams (Maurice Sklar, F. E. Wiancko, John Baxter)
Walter Anthony Wojciechowski (S. B. Stewart, Fred Smith, R. F. Bennett)
Douglas Robert Yahnke (Klaas van der Weg, C. H. Johnson, R. E. Woods)
Malcolm Arthur Young (G. E. Olson, H. M. Buchner, S. E. Giulio)

TRANSFER TO ACTIVE

John Moore Armstrong (R. M. Bradley, E. J. Gemmill, G. N. Shell)
James S. Bigelow (Rayman Sturdevant, J. G. Parker)
Elmer Alexander Blomerth, Jr. (L. W. Gardner, L. F. Melchior, E. A. Malone)
Gunnar Bodvarsson (H. R. Joesting)
Lynn Woodrow Cobena (R. L. Lay, O. B. Hocker, E. H. Shannon)
Cecil Edward Dalik (H. J. Kidder, L. E. Twining, Louis Castelli)
Everett Fay Damon (Andrew Gilmour, F. F. Campbell, C. M. Ross)
John Frank Fuller (F. J. Agnich, Robert Dyk, J. C. Karcher)
Walter William Garvin (C. H. Dix, F. A. Hale, S. C. Stoneham)
Raymond Stanley Kittlitz (P. M. Tucker, J. I. Walton, Dwight Ward)
Eddie Lee Koenning (W. L. Crawford, R. B. Pratt, V. J. Hunzicker)
Donald Robert Oksa (J. F. Johnson, W. W. Hawthorne, A. E. McKay)
Thomas Ortiz (A. J. Barthelmes, D. F. Warner, R. F. Aldredge)
Chester Roland Partridge (F. E. Ittner, C. E. Reel, T. E. Dennis)
Elwin Merrill Peacock (R. F. Bennett, S. B. Stewart, C. H. Green)
Justus Verner Price (N. W. Mann, J. W. Thomas, R. F. Dundon)
Donald John Salt (E. D. Westrick, N. B. Keevil, J. E. Blanchard)
Charles Alfred Shannon (W. P. Lawrence, T. F. Southgate, Andrew Gilmour)
Jack Kitson Smith (E. J. P. van der Linden, E. B. Lindsey, A. A. Fitch)
George Lutfi Sorour (Oscar Weiss, Bruno Martina, H. P. Downey)
Arthur Lamoreaux Stauffer (C. B. Smith, Richard Williams, V. H. Waddell)
Joseph W. Thornton (F. F. Campbell, Andrew Gilmour, C. M. Ross)
Harmen Jan van der Plaats (A. van Weelden, G. Kok, F. A. Van Melle)
Johannes Jacob van Bekkum (G. H. Westby, E. van der Linden, A. A. Fitch)
Val Graham Winston (W. H. Amis, Jr., E. D. Alcock, J. H. Frasher)

Vernon Everett Whitney (R. C. Kendall, R. F. Christy, H. L. Thomsen)
Paul Clarence Wuenschel (R. M. Tripp, M. B. Dobrin, J. L. Worzel)

TRANSFER TO ASSOCIATE

William Cyril Abbott (J. R. Randolph, O. B. Manes, L. K. Mower)
George Vernon Keller (B. F. Howell, Jr., L. O. Bacon, H. R. Joesting)
Roy Leonard Nix (J C. Menefee, O. H. Armstrong, W. F. Lechtenberg)
Earl Estes Outcalt (C. R. Holmes, M. H. Wilkening, J. A. Tavelli)
Joseph Benoit Prendergast (R. H. Rainey, C. M. Moore, Jr., C. H. Green)
Edward William Racek (References waived by Executive Committee)
Andres Ramirez (A. Garcia Rojas, J. W. Thomas, J. C. Hollister)
James Bernard Sheehan (J. C. Hollister, R. C. Holmer, C. H. Green)
Howard Addison Slack (W. C. Krumbein, G. D. Garland)
James Adolph Westphal (W. B. Agocs, W. E. Pugh, R. L. Frossard)
Donald Everett Wilson (R. F. Bennett, C. B. Smith, S. B. Stewart)

ANNOUNCEMENTS

ANNOUNCEMENT OF MIDWESTERN MEETING

The Seventh Annual Midwestern Exploration Meeting will be held November 12 and 13, 1953, at the Hotel Adolphus, Dallas, Texas. It is sponsored by the Dallas, Fort Worth, Midland, Oklahoma City, Shreveport, and Tulsa Sections of the Society of Exploration Geophysicists. The Permian Basin Geophysical Society is in charge of arrangements, and the Dallas Geophysical Society will serve as host. Registration will begin Wednesday evening, November 11, in the lobby of Hotel Adolphus. Technical sessions will be held Thursday and Friday in the hotel ballroom, and the Safety Session will be presented by the Standing Committee on Safety in the Cactus Room of the hotel on Thursday evening. The meeting will close with the annual dance on Friday night.

Ample accommodations have been reserved by the Adolphus, and members submitting applications for housing on the official business reply postal card will receive priority. Official announcements of this meeting have been mailed to all members in good standing in North America. There will be no exhibits.

PACIFIC COAST REGIONAL MEETING

NOVEMBER 6, 1953—9:00 A.M.

BILTMORE HOTEL—LOS ANGELES, CALIFORNIA

This meeting is held in conjunction with meetings of the Pacific Section A.A.P.G. and S.E.P.M. as a joint session. In addition, the annual conference of the Institute of Geophysics of the University of California is being held immediately prior to the S.E.G. session and a joint program will be arranged.

S.E.G. TECHNICAL SESSION—FRIDAY, NOVEMBER 6

9:00–11:30 A.M.—GALERIA ROOM

1. Radioactivity Measurements in the Los Angeles Basin
   Wayne Hoyleman and W. L. Morris, Hoyleman-Morris Consultants
2. One Dimensional Transducers for Seismic Models
   Leon Knopoff and Glenn Brown, Institute of Geophysics, UCLA
3. Observed Mohorovicic Reflections in Blasts and Local Earthquakes
   George Shor, Seismological Laboratory, California Institute of Technology
4. Safety, a Responsibility of Management
   Carl H. Gerdes, Western Geophysical Company of America
5. Recording of Seismic Waves in Bore Holes
   E. T. Howes, United Geophysical Company

6. Forces and Effects of Explosives in Submarine Geophysical Exploration
   Frank J. Hortig, State Lands Commission, State of California
7. Highlights of Seismic Exploration in California
   Maurice Sklar, Union Oil Company

S.E.G. LUNCHEON MEETING—12:00–2:00 P.M.

Invited address by Dr. David Griggs, Institute of Geophysics, UCLA
"Reflections on Some Hypotheses of Mountain Building"

JOINT TECHNICAL SESSION WITH THE A.A.P.G.

2:00–4:30 P.M.

8. Feature Speaker
   Roy L. Lay, Manager of the Geophysical Division, The Texas Company, Houston, Texas
9. The Microlog Continuous Dipmeter
   C. F. Gallagher, Schlumberger Well Surveying Corporation
10. Geophysical History of South Cuyama Oil Field
    John W. Mathews, Richfield Oil Corporation
11. Case History of Wild Goose Gas Field
    W. L. Matjasic, Honolulu Oil Corporation

The annual conference of the Institute of Geophysics of the University of California will be held November 4 and 5 at UCLA and will include 24 technical papers on various subjects, among which are a symposium on the Capricorn Expedition and its results in Pacific basin investigations, and a session devoted to geophysical modeling.

A.A.P.G. and S.E.P.M. technical sessions will be held Thursday, November 5, at the Biltmore Hotel. A semi-formal dinner dance will be held at the Biltmore Hotel Friday evening, November 6.

ANNOUNCEMENT OF EASTERN REGIONAL MEETING

The Eastern Regional Meeting will be held concurrent with the Annual Meeting of the American Association for the Advancement of Science on December 29, 1953 in the Mechanics Building, Boston, Massachusetts. For the information of AAAS members in the Society, the SEG is affiliated with the Association under Section E, Geology and Geography. This is the first meeting with AAAS, made possible by the affiliation which was consummated in 1952.

Inauguration of this meeting was made possible through the work of the SEG Eastern Regional Program Committee, under the chairmanship of Ralph B. Ross. Dr. L. Don Leet will be the chairman of the meeting and will be in charge of all the local arrangements. Dr. Roland F. Beers will take care of AAAS liaison, and Dr. Frank Press will assist Mr. Ross in preparation of the technical program.

Official announcement of the meeting, with hotel information and registration forms, has been mailed to members of the Society. Information regarding exhibits may be obtained from Mr. R. L. Taylor, The American Association for the Advancement of Science, 1515 Massachusetts Avenue N.W., Washington 5, D. C.

ANNOUNCEMENT OF ANNUAL MEETING

The 24th Annual Meeting of the Society of Exploration Geophysicists will be held in St. Louis, Missouri, on April 12–15, 1954. Headquarters will be in the Hotel Jefferson, where officers and committees may meet, and technical sessions will be held in the Opera House of the St. Louis Municipal Auditorium. As in previous years, this meeting will be conducted jointly with the annual meetings of The American Association of Petroleum Geologists (39th) and the Society of Economic Paleontologists and Mineralogists (28th).

Tentatively, the schedule of events will follow the custom of previous years. Registration will begin Sunday, April 11, in the Jefferson Hotel, and SEG members are particularly urged to register Sunday if possible. Monday, April 12, will be "Exhibits Day," with the registration booth moved to

the Auditorium, and delegates will be invited to spend the day viewing the extensive exploration science exhibits in the Convention Hall portion of the building. Also on Monday the Executive Committee and Council will meet, and the Safety Committee program will be presented at the Jefferson Hotel. S.E.G. field trips may also be scheduled for Monday.

The tentative program of technical sessions provides for a joint session with AAPG and SEPM on Tuesday morning for presentation of honors and presidential addresses. Tuesday afternoon the SEG will present seismic papers. Wednesday morning the three groups will hold a joint technical session, and SEG will present gravity and magnetics papers Wednesday afternoon. A mining geophysics program is scheduled for Thursday morning, with another seismic session that afternoon. On Thursday night the meeting will close with the joint annual dinner dance at the Jefferson Hotel.

Housing arrangements have been provided by the St. Louis Convention Reservations Bureau. The formal announcement, containing an official Application for Housing Accommodations form, has been mailed to all members in good standing. Members are requested to notify the business office if this announcement has not been received by December 15, 1953. Further details are given in the official mailed announcement.

ANNOUNCEMENT REGARDING CHANGES OF ADDRESS

Members whose duties require frequent moves may obtain more reliable delivery of their *Geophysics* by listing their headquarters addresses with the Society. Because the journal is issued quarterly the post office is unable to provide the directory service enjoyed by publications issued more frequently. Therefore, notice of a member's new address given the post office does not guarantee that his next issue of *Geophysics* will be forwarded. Issues directed by the Society to members who have moved are returned to the business office by the post office, with notice of new address. Return postage is paid by the Society, and these issues are sent to the addresses given by the post office. In the event an issue is returned from the second address, undeliverable, the member's name is removed from the mailing list pending receipt of his notice of address.

By listing your company's headquarters or district office address you can be assured more prompt delivery of your *Geophysics*.

THE TORONTO GEOPHYSICAL DISCUSSION GROUP

A geophysical discussion group has been informally assembled in Toronto and two meetings have been held, the first on May 12th and the second on June 8th.

The membership of this group consists of persons, resident in the Toronto area, who are actively engaged in geophysical exploration. Because of the nature of the activities of its membership the attention of the group is largely directed toward mining geophysics problems.

One of the prime aims of this organization is the improvement of public relations. The members of the mining community whose job it is to integrate geophysical methods into their exploration programs, are largely uninformed as to the variety, applicability and limitations of these methods. Hence the need is great for dissemination of basic information concerning the available mining geophysical techniques.

No less serious a problem is the marked decrease in the number of students who are working towards careers in mining geophysics. The discussion group feels that it can help to improve the situation by talking before high school graduating classes and university freshmen to inform them of the opportunities that geophysics may hold for them. The medium of summer employment also offers an excellent opportunity to acquaint students with geophysics.

A close association will be maintained between the discussion group and the Student Section of the SEG at the University of Toronto. Representatives from the latter organization have been invited to participate in the meetings of the group. In addition, members of the group can provide speakers on specific phases of exploration geophysics for meetings of the Student Section.

Meetings of the discussion group are held on the second Monday of each month. The group

would be pleased to have visiting members of the SEG attend these monthly meetings, providing that they are willing to accept the risk of being asked to talk on their favorite topic. The time and place of meeting may be determined by contacting either Dr. H. O. Seigel (Chairman), Suite 12, 25 Melinda Street, or Dr. S. H. Ward (Secretary), McPhar Geophysics Ltd.

PERMIAN BASIN GEOPHYSICAL SOCIETY

LIST OF VELOCITY SURVEYS

The Permian Basin Geophysical Society announces the completion and availability of a new edition of "List of Velocity Surveys" covering the area of West Texas, Southeast New Mexico, North Central Texas, Texas and Oklahoma panhandles, and the San Juan Basin.

This new edition has the following features:

1. Composite of all surveys previously listed in the Society's original printing of March 1951, three supplements published in 1951 and 1952, and 121 additional surveys conducted since the last supplement.
2. A total of 677 surveys now listed.
3. One county per page used in all active counties
4. Bound in a leather three-ring loose leaf notebook, enabling pages to lie flat.
5. Size of page reduced to $8\frac{1}{2} \times 11$ inches.

The Society, at regular intervals, will publish additions and corrections which will be sent to the subscribers. And whenever enough surveys have been conducted in any one county to fill out a page, a new print of this page will be made and sent to each subscriber.

The velocity index map published in 1951 (scale 1:500,000) which covers the entire area, except for the San Juan Basin, has also been kept up to date and is now available. Each well is located with notation of index number, depth of survey and lowest formation surveyed. This map comes in two parts—a North half and a South half with dividing line at the Matador Arch.

If ordering more than one copy of "List of Velocity Surveys" it is requested that the *permanent* address for each point of distribution be given; otherwise all future supplements will be sent to the one address given. Orders should be addressed to Permian Basin Geophysical Society, Box 1018, Midland, Texas.

NEW A.G.I. EXECUTIVE

The American Geological Institute is pleased to announce that it has secured for its executive directorate the services of Mr. C. B. Hunt, currently chief of the General Geology section of the United States Geological Survey with headquarters in Denver, Colorado. Mr. Hunt assumed his duties on September 1, 1953. In accordance with reorganization of the Institute, which is associated by charter with the Division of Earth Sciences (formerly the Division of Geology and Geography) of the National Research Council, the past executive director, Dr. Robert W. Webb, retired from the post on August 31, 1953.

President Carey Croneis and the members of the Executive Committee are certain that the profession will receive the appointment of Mr. Hunt not only with approval, but with the conviction that the future of A.G.I. is bright with a geologist of Mr. Hunt's stature and accomplishments, both administrative and professional. With the continued active cooperation of an ever increasing number of scientists, Mr. Hunt will be able to continue and expand the new program of the A.G.I. The Executive Committee is particularly appreciative of the efforts of A.G.I. Secretary-Treasurer H. S. Ladd in the search for and selection of the new executive. The cooperation of the National Academy of Sciences-National Research Council, and the assistance of the Council Chairman, Dr. W. W. Rubey, is also acknowledged in the final selection of Mr. Hunt for the assignment.

COLORADO SCHOOL OF MINES INDEX

The Colorado School of Mines has revised and published a new index to cover all publications from this mineral engineering college.

Announcement of the printing of the 89-page book was made by LeRoy W. Goodwin, director of the department of publications.

The index is of particular value since it lists publications that are out of print and can be viewed only in the "Mines" library as well as books available for distribution.

Included is a lengthy listing, by subject, of the mineral industry topics covered in the college's Quarterly and in independent "Mines" publications. There is also an index of authors and a listing of theses titles covering the years since 1896.

In addition the college has compiled a listing of only those publications which are available for sale. Interested persons can obtain either the complete index or this specialized listing free of charge by writing the Department of Publications at the Colorado School of Mines, Golden, Colorado.

THANKS

To relieve the year-end rush the business office began sending members their 1954 dues statements on July 14, 1953. Each day thereafter the statements were sent to a small number of members, in alphabetical order.

Through the cheerful cooperation of our members the task was completed September 30, 1953, earlier than we have heretofore started mailing the statements. The response has been most gratifying. Although the dues are not "due" until January 1, 1954, many members have graciously paid in advance. So many have written notes of approval with their payments the office has been unable to acknowledge all of them. So far the office has received no objections to the plan. On December 1, 1953, a second notice will be sent to all who have not responded.

PERSONAL ITEMS

Members of the Society are invited to notify the business manager, in care of the Society, at 624 South Cheyenne, Tulsa 3, Oklahoma, of any change in their positions or companies for announcement in this section of their journal. Members are further invited to check with the public relations departments of their companies to assure that *Geophysics* is on their mailing lists to receive publicity releases.

WILLIAM E. ALLEN has been elected the first president of the Houston Students Section, S.E.G. Announcement of the election was made by EUGENE W. FROWE, chairman of the Standing Committee on Student Membership, in advising of the Houston Students Section organization meeting on August 24, 1953.

J. C. ROLLINS has been named head of the sales department of the newly-formed Aero Service Corp. (Mid-Continent) at Tulsa, Oklahoma, it has been announced by Aero Service Corporation, Philadelphia, the parent company. The new organization, formerly Frost Airborne Surveys Corp., will provide aerial exploration and mapping service in the central United States. W. B. AGOCS, formerly head of the department of geophysics at The University of Tulsa and presently chief geophysicist for the parent firm, will serve as consultant for the firm in geophysical matters.

NEAL J. SMITH, formerly with The California Company in New Orleans, is now research geophysicist with Chevron Oil Co., Houston, Texas.

GORDON D. CLOEPFIL, supervisor for Geophysical Service Inc., has been transferred to Billings, Montana. R. H. RAINEY, supervisor, has transferred from Geophysical Service International Corp. in Calgary, to Geophysical Service Inc., Midland, Texas.

EDMUND BORYS has resigned as manager of exploration for El Capitan Oil Co., and has opened offices in Midland, Texas, as consulting geologist and geophysicist.

J. W. HOOVER, vice president in charge of exploration for The California Company, New Orleans, has resigned that position to become president of Chevron Oil Company. Chevron is a wholly-owned

subsidiary of the Standard Oil Company of California and is being organized to do geophysical work for the Standard of California group.

H. E. STOMMEL, formerly seismologist for The California Company, has been transferred to the Chevron Oil Company, Houston, Texas, as manager of seismic operations.

W. A. BRAMLETTE has been appointed assistant chief geologist of The Carter Oil Company.

J. S. WELBOAN, JR. is now assistant division manager of the geophysical division, producing department of the Texas Company, Houston. V. E. CHILD replaces Mr. Welboan as assistant to the division manager in the Houston office. T. L. KUNKEL, formerly supervisor in the West Texas division, has moved from Fort Worth to Houston to become assistant to the division manager.

G. ROY BROTHERHOOD has become vice president and manager of operations for Canpet Exploration Ltd., Calgary, Alberta.

JOHN O. GALLOWAY was recently elected president of the Calgary Petroleum Club for 1953–1954.

THE SOCIETY OF ECONOMIC PALEONTOLOGISTS AND MINERALOGISTS has started plans to form a Gulf Coast section through naming a steering committee headed by Stuart A. Levinson as temporary chairman; Charles W. Stuckey and Fred L. Smith, Jr., vice-chairmen; Jack O. Colle, Secretary; Frank V. Stevenson, treasurer; and Morton B. Stephenson, vice-treasurer, form the committee.

N. J. LEA has become supervisor of field operations for the Houston geophysical division of The Texas Company. He was formerly seismologist in the company's Tulsa office.

H. W. BROWN has become manager of exploration for The Carter Oil Co. He was formerly chief geophysicist.

DAVID E. REED is now geologist and geophysicist for Kewanee Oil Co., Tulsa, Oklahoma.

C. E. RIDDELL is now exploration manager for The British American Oil Producing Co., northwestern division, Denver, Colorado. He was formerly division geophysicist for Union Oil Company.

A. B. BRYAN has returned to Tulsa, Oklahoma, where he is manager of the geophysical division and coordinator of research for exploration and production activities of The Carter Oil Co. He was formerly in the production research department of Standard Oil Development Co. in New York.

E. G. DOBRICK, JR., formerly with The California Company, is now chief geophysicist for Standard Oil Company of California.

DONALD W. ST. CLAIR is now an independent operator and consulting geologist in Midland, Texas.

The Rice Institute, Houston, Texas, announces the appointment of CAREY CRONEIS as Provost and Harry Carothers Wiess Professor of Geology. Dr. Croneis was president of Beloit College.

C. W. PAYNE, geophysical consultant of Fort Worth, announces the association of Mr. KIRBY J. WARREN in a firm to be known as Payne & Warren, Geophysical Consultants, with offices in the Continental Life Building, Fort Worth, Texas. Mr. Warren was formerly geophysicist with Sinclair Oil and Gas Co. Southern Division office in Fort Worth.

J. B. JACKSON, formerly of The Hague, Holland, has joined Shell d'Arcy Petroleum Development Co. Ltd. at Owerri, Southern Nigeria, British West Africa.

R. A. BRODING, former research associate in the Magnolia Petroleum Co. Field Research Laboratories, has become vice-president of Century Geophysical Corp., Tulsa, Oklahoma.

FOSTER J. SCHEMPF, formerly manager of exploration of Stanolind Oil & Gas Co., has been elected vice-president in charge of exploration.

HELMUT KLAUS, of Klaus Exploration Company, has been elected president of the Lubbock Geological Society, W. C. HAYES, JR. is vice-president, and JACK M. REED is secretary-treasurer of the society.

DONALD M. DAVIS has become manager of the geological and exploration department of The Pure Oil Co. to succeed LYNN K. LEE, who retired June 30, 1953.

PIETER S. STOUTJESDYK has joined the staff of Geophysical Service Inc. as technical assistant to CURTIS H. JOHNSON, manager of the Marine Division. Mr. Stoutjesdyk was formerly with Shell Oil Company.

H. V. CROWDER, formerly with Seismic Explorations, Inc. as field supervisor, is now district supervisor with Nance Exploration Company in Billings, Montana.

C. D. ROEMER and OSCAR J. KASTNER, JR. have formed Consolidated Geophysics Co., Boulder Building, Tulsa, Oklahoma.

GEORGE R. ROGERS has resigned his position as geophysical engineer for Phelps Dodge Corp. to accept a similar position with Bear Creek Mining Co., Rocky Mountain district office, 1219 California St., Denver 4, Colorado.

RICHARD A. POHLY was recently elected a vice-president of Seismograph Service Corp., Tulsa, Oklahoma. R. S. FINN has become vice-president of Lorac Service Corp. and manager of Lorac Maritime Corp., SSC subsidiaries, and F. B. LEEDY has been elected a director and treasurer.

GEORGE J. BLUNDUN has become chief geophysicist of Federated Petroleums Ltd. and Home Oil Co. Ltd. He was formerly chief geophysicist for Northwest Seismic Surveys, Ltd.

D. T. GERMAIN-JONES has been elected president of the European Association of Exploration Geophysicists.

A. W. FARMILO has been appointed chief geologist of Western Leaseholds Ltd., Calgary, Alta., Canada.

WALTER OSTERHOUDT, consultant, Durango, Colorado, has been elected second vice-president of the Four Corners Geological Society. Mr. Osterhoudt was active in organizing the S.E.G. Houston Section, serving as one of its first officers.

SOCIETY OF EXPLORATION GEOPHYSICISTS
CONSTITUTION

Article I.	Name	Article X.	Meetings
Article II.	Object	Article XI.	Local Sections
Article III.	Membership	Article XII.	Districts
Article IV.	Code of Ethics	Article XIII.	Affiliated Societies
Article V.	Election, et cetera, of Members	Article XIV.	Committees
Article VI.	Officers	Article XV.	Business Manager
Article VII.	Duties of Officers	Article XVI.	Review by Members
Article VIII.	Council	Article XVII.	Bylaws
Article IX.	Executive Committee	Article XVIII.	Amendments to the Constitution

CONSTITUTION

(As amended to August 26, 1948)

Article I. Name

Section 1. The Society shall be called the "Society of Exploration Geophysicists."

Article II. Object

Section 1. The objects of this Society shall be to promote the science of geophysics especially as it relates to exploration and research, to foster the common scientific interests of geophysicists, and to maintain a high professional standing among its members.

Article III. Membership

Section 1. The membership of this Society shall consist of persons elected and qualified in accordance with the Constitution and Bylaws of this Society at the time of such election.

Section 2. The membership of this Society shall consist of Honorary Members, Active Members, Associate Members, and Student Members.

Section 3. To be eligible to election to Honorary Membership a person shall, in the unanimous opinion of the Standing Committee on Honors and Awards and the Council, have made a distinguished contribution to geophysics or a related field which warrants exceptional recognition.

Section 4. To be eligible to election to Active Membership an applicant must have been actively engaged in practicing or teaching geophysics or a related field for not less than eight years (up to four years as a student in a recognized college or university may be counted toward this total) of which at least three years must have involved work of a responsible nature calling for independent judgment and the application of geophysical or geological principles.

Section 5. To be eligible to election to Associate Membership, an applicant must be actively interested in geophysics.

Section 6. To be eligible to election to Student Membership an applicant must be a graduate or undergraduate student in good standing in residence at a recognized university or college.

Section 7. An Honorary Member or Active Member shall enjoy all privileges of the Society. He shall be eligible to hold any office, to vote on all matters submitted to the membership, to petition the Council or Executive Committee on any matter, to sponsor applicants for membership and to publish his affiliation with the Society.

Section 8. An Associate Member or Student Member shall be entitled to attend the meetings of the Society, to receive its Journal and to purchase its publications, on the same terms as an Active Member. He shall have none of the other privileges of membership and in publishing his affiliation with the Society shall clearly indicate his grade of membership.

Article IV. Code of Ethics

Section 1. Membership of any class shall be contingent upon conformance with the established principles of professional ethics.

Article V. Election, Resignation and Expulsion of Members

Section 1. The method of election to the various grades of membership shall be as set forth in the Bylaws.

Section 2. Any member in good standing may resign from the Society at any time as set forth in the Bylaws.

Section 3. Any member may for the good of the Society be suspended or expelled from the Society at any time as set forth in the Bylaws.

Article VI. Officers

Section 1. The officers of the Society shall be a President, a Vice-President, a Secretary-Treasurer, and an Editor. Officers shall be elected in the manner prescribed in the Bylaws for a term of one year with the exception of the Editor, whose term shall be two years.

Section 2. Election of officers shall be by secret mail ballot. On the ballot shall be printed the nominees for each office arranged in alphabetical order.

Section 3. The Standing Committee on Nominations shall nominate, in the manner prescribed in the Bylaws, two candidates for each office to be filled. Further nominations may be made by petition as set forth in the Bylaws.

Section 4. The officers shall assume the duties of their respective offices immediately after the close of the Annual Meeting following their election.

Section 5. No officer shall be eligible for election to the same office for two consecutive terms.

Section 6. In case of a vacancy in any office, other than the President's, the Executive Committee shall select a successor to serve until the close of the annual meeting following this appointment.

Article VII. Duties of Officers

Section 1. The President shall be the presiding officer at all the meetings of the Society, shall take cognizance of the acts of the Society and of its officers, shall appoint such standing committees and special committees as are required for the purposes of the Society, and shall delegate members to represent the Society. He may, at his option, serve on, and may be chairman of, any committee. He shall prepare an address to be given before the members of the Society at the Annual Meeting.

Section 2. The Vice-President shall assume the office of President in case of a vacancy from any cause in that office and shall assume the duties of President in case of the absence or disability of the latter. He shall also be responsible for all national meetings of the Society.

Section 3. The Secretary-Treasurer shall assume the duties of the President in case of the absence of both the President and Vice-President. He shall have charge of the financial affairs of the Society and shall annually submit reports as Secretary-Treasurer covering the fiscal year, which he shall arrange to have published in the next regular issue of the Journal of the Society. Under the direction of the Council, he shall arrange for the receipt and disbursal of all Society funds. He shall cause an audit to be prepared annually by a public accountant at the expense of the Society. He shall give a bond, and shall cause to be bonded, all employees to whom authority may be delegated to handle Society funds. The amount of such bonds shall be set by the Council and the expense shall be borne by the Society.

Section 4. The Editor shall be in charge of the editorial business, shall submit an annual report of such business, shall have authority to solicit papers and material for the regular Society publication and for special publications, and may accept or reject material offered for publication. He may appoint associate, regional, and special editors.

Article VIII. Council

Section 1. The Council of the Society shall consist of the officers, the Past President, the Past Prior President, and all elected District Representatives.

Section 2. The Council shall be the governing body of the Society and subject to the provisions of the Constitution and Bylaws shall have full control and management of the affairs and funds of the Society.

Section 3. A joint meeting of the outgoing and incoming Councils shall be held at the call and under the chairmanship of the newly elected President during or within seven days after the Annual Meeting of the Society. At this joint meeting the Councils shall hear reports from all officers and committees and review the activities of the Society for the past year. With the advice of the outgoing Council, the incoming Council shall conduct any necessary business and issue instructions or recommendations to any officer or committee, subject to the provisions of the Constitution and Bylaws. All committee chairmen shall attend this meeting, but, as chairmen, shall have no vote.

Section 4. At the call of the President or a majority of the Council members, and after written notice to all Council members, the Council may meet at any time.

Section 5. A quorum at any meeting of the Council shall consist of six Council members.

Section 6. Unless otherwise provided by the Constitution, all actions by the Council shall require a majority vote of the members present.

Article IX. Executive Committee

Section 1. The Executive Committee shall consist of the President, the Vice-President, the Secretary-Treasurer, the Editor, and the Past President.

Section 2. When the Council is not in session the Executive Committee shall have full authority, subject only to prior instructions by the Council, to exercise all powers of the Council.

Section 3. All actions of the Executive Committee shall require a majority vote of all members of the Committee.

Section 4. The Executive Committee may vote on any matter either by mail or in person.

Article X. Meetings

Section 1. The Society shall hold at least one meeting of the members each year, this meeting to be known as the Annual Meeting. One session of this meeting shall be a Business Meeting, at which reports of the officers and committees shall be read and the result of the mail ballot for officers announced.

Section 2. The Annual Meeting shall be held at a time and place designated by the Executive Committee.

Section 3. Additional meetings of the Society may be called by the Executive Committee.

Article XI. Local Sections

Section 1. Local sections, consisting of members of the Society and other persons engaged in geophysics or a related field residing within an appropriate distance of a central point, may be organized as provided in the Bylaws.

Section 2. Each local section shall assist in carrying out the objectives of the Society within the territory assigned to the section by the Council.

Section 3. Each local section shall have one District Representative if among its members there are less than seventy-five Honorary Members and Active Members of the Society in good standing, two District Representatives if more than seventy-five and less than one hundred fifty, or three District Representatives if more than one hundred fifty.

Section 4. The District representatives shall be elected from among the Honorary Members and Active Members of the Society in good standing for terms stated and in the manner prescribed in the Bylaws and shall not be eligible for two consecutive terms.

Article XII. Districts

Section 1. The Council shall divide the area of the continental United States, not assigned to local sections, into not more than seven districts. Council may designate districts outside the area of the continental United States.

Section 2. Each district shall have for each seventy-five Active Members of the Society, who are not members of a local section, one District Representative, who shall be appointed by the President for a term of one year expiring at the close of the Annual Meeting.

Article XIII. Affiliated Societies

Section 1. The Council may arrange for affiliation of the Society with any duly organized groups or societies.

Section 2. The terms of affiliation must provide that the Society shall have the right to dissolve such affiliation at any time, subject only to the payment of any sums it may legally owe the affiliated group or society.

Article XIV. Committees

Section 1. In addition to the Executive Committee, there shall be appointed standing committees to further the purposes of the Society.

Section 2. The duties of the standing committees and the method of their appointment shall be in accordance with the Bylaws.

Section 3. The President may at any time appoint special committees for such purposes as he may deem fit.

Section 4. The terms of all special committees shall expire at the close of the Annual Meeting following their appointment.

Article XV. Business Manager

Section 1. The Council may employ a business manager for the Society and pay him such salary and other compensations from the Society's funds as they deem advisable.

Section 2. The business manager shall provide a bond appropriate in amount, the cost to be borne by the Society.

Section 3. The business manager shall, under the supervision of the Secretary-Treasurer, perform such duties as the Council may assign him.

Section 4. The Council may discharge the business manager at any time.

Article XVI. Review by Members

Section 1. All acts of the officers, Council, and committees of the Society shall be subject to review by the members.

Section 2. Proposals to change any decision, policy, or procedure of any officer, the Council, or any committee shall be submitted in writing to the President and signed by at least twenty-five Honorary and Active Members in good standing.

Section 3. Upon receipt of such a petition with a sufficient number of valid signatures, the President shall advise the Council and the officer or committee involved.

Section 4. Should the officer or committee involved be unwilling to comply with the petition, it, together with a discussion by the proposer and the officer or committee involved, shall be published in the next issue of the Society's journal.

Section 5. Within thirty days after publication in the journal, the petition shall be submitted to the membership by mail ballot by the President. A majority of the ballots returned within thirty days after being mailed by the President shall be decisive. Should the vote favor the petition, it shall be complied with, within the limitations imposed by the Constitution and Bylaws, as promptly as practicable.

Article XVII. Bylaws

Section 1. The Council shall make such Bylaws not in conflict with the Constitution, as it may deem necessary for the proper government of the Society. The Council may amend the Bylaws at the annual joint meeting by an affirmative vote of two-thirds of the members of the incoming Council present. All proposed amendments must, however, be published in the Society's journal before being submitted to the Council.

Article XVIII. Amendments to the Constitution

Section 1. Amendments to this Constitution may be proposed by any ten members of the Society, by any officer of the Society, or by a Constitutional Committee appointed by the President.

Section 2. Any proposed amendment shall be submitted to the President in time for publication in the Society's journal prior to the Annual Meeting.

Section 3. At the annual joint meeting of the Council, all proposed amendments received since the previous Annual Meeting, shall be considered. Those receiving approval from a majority of the members of the incoming Council present shall be submitted by mail ballot, arranged by the Secretary-Treasurer, to the entire membership of the Society within sixty days. If a majority of the ballots returned within sixty days of their mailing favor the proposed amendment, it shall become effective at the expiration of this sixty days. All amendments shall be reported in the Society's journal.

BYLAWS

Article I. Publications
Article II. Election of Honorary Members
Article III. Election of Active, Associate and Student Members
Article IV. Dues
Article V. Resignation of Members
Article VI. Expulsion of Members
Article VII. Election of Officers
Article VIII. Local Sections
Article IX. Finances of Local Sections
Article X. Standing Committees

BYLAWS

(As amended to March 23, 1953)

Article I. Publications

Section 1. The Society shall publish a journal entitled *Geophysics*.

Section 2. The journal shall be published at intervals designated by the Executive Committee.

Section 3. All reports to the Society by its officers and committees shall be published in the journal. All members of the Society shall be presumed to have due notice of all Society matters published in the journal. Each issue shall contain a membership list of all standing and special Committees.

Section 4. Original papers, reviews, abstracts, notes or letters containing information deemed by the Editor to be of interest to the members of the Society shall be published in the journal. The Editor shall be the sole judge of whether such material is to be published.

Section 5. The subscription rate of the journal shall be $9.00 ($9.50 foreign) per year to nonmembers and $4.50 per year to members. The first $4.50 of the annual dues of each dues paying member shall be set aside for the payment of his subscription to the journal. Members of affiliated societies shall be entitled to receive the journal upon payment of a fee equivalent to the dues charged to an associate member.

Section 6. The Council may at its annual joint meeting authorize the printing of special publications to be financed and distributed in a manner approved by the Council.

Article II. Election of Honorary Members

Section 1. The Standing Committee on Honors and Awards may submit to the President ninety

days before the Annual Meeting the names of any person or persons they deem eligible to election as an Honorary Member. Their report shall explain the basis of their recommendation.

SECTION 2. The President shall submit copies of any such reports to all members of the Council not less than sixty days before the Annual Meeting.

SECTION 3. The Council members shall consider all such reports and vote by mail thirty days before the Annual Meeting. Unanimous action by those voting shall be required to elect any person as an Honorary Member.

ARTICLE III. ELECTION TO ACTIVE, ASSOCIATE AND STUDENT MEMBERSHIP

SECTION 1. An applicant for election to Active, Associate or Student Membership shall submit to the business manager of the Society an application setting forth in detail his education and experience. The application shall list the names and present addresses of persons who can verify the statements given therein. It shall list not less than three Active Members or Honorary Members of the Society, in good standing, who are personally acquainted with the training or experience of the applicant. This application shall be open to inspection at any time.

SECTION 2. The Executive Committee may waive the requirement of references from members of the Society for geographical or other reasons, if the applicant is otherwise eligible and furnishes other satisfactory references.

SECTION 3. The business manager shall write to all references for verification of the applicant's statements. All replies from references shall be considered confidential and shall not be disclosed except to the Executive Committee, without the references' prior written consent.

SECTION 4. The business manager, upon receipt of the replies from all references, shall submit to the Executive Committee the application and the replies from the references.

SECTION 5. Should the Executive Committee unanimously approve and sign the application, the applicant's name shall be published in the next regular issue of the Society's journal for approval by the membership at large. If no objection to his election is received by the President within thirty days after this publication, he shall be pronounced elected. The business manager will notify the applicant. In the case of applicants for Student Membership publication is not required. The student member shall be pronounced elected when approved by the Secretary-Treasurer.

SECTION 6. An applicant for membership, upon being notified in writing of his election, shall pay full dues for the current year and upon making payment shall receive a membership card and the regular Society publications for the year of entrance. Unless payment of dues is made within thirty days by those living within the continental United States and within ninety days by those living elsewhere the Executive Committee may rescind the election of the applicant.

SECTION 7. An Associate or Student Member may seek transfer to Active Membership by supplying added information to show that he has become eligible to election to Active Membership. The transfer shall be handled in the same manner as election to Active Membership. The Standing Committee on Membership may of its own initiative secure the necessary added information and submit it to the Executive Committee.

ARTICLE IV. DUES

SECTION 1. Honorary members shall not be required to pay dues and shall receive the journal and other publications without charge.

SECTION 2. The annual dues of an Active or Associate Member of the Society shall be seven dollars and fifty cents ($7.50), which includes the cost of one subscription to the Society's journal.

SECTION 3. The annual dues of a Student Member of the Society shall be four dollars and fifty cents ($4.50), which includes the cost of one subscription to the Society's journal.

SECTION 4. Annual dues shall be payable in advance on January 1 of the calendar year. A bill shall be mailed to each Active, Associate or Student Member before that date, stating the amount of annual dues and the penalty for default. The Society's journal shall be withheld from members pending payment of dues, and Active Members failing to pay by ten days prior to the Annual Meeting shall have their votes in the annual mail ballot disqualified. Members in arrears shall lose all privileges of membership until such arrears are met.

Article V. Resignation of Members

Section 1. Any member of the Society may resign at any time. Such resignation shall be submitted in writing to the Council.

Section 2. Any member who resigns under the provisions of Section 1 of this Article ceases to have any rights in the Society and ceases to incur further indebtedness to the Society.

Section 3. Any person who has ceased to be a member under Section 1 of this Article may be reinstated by unanimous vote of the Executive Committee subject to the payment of any outstanding dues and obligations which were incurred prior to the date when he ceased to be a member of the Society.

Article VI. Expulsion of Members

Section 1. Any member more than two years in arrears shall be dropped from the Society by the Executive Committee.

Section 2. Any member who is dropped under the provisions of Section 1 of this Article ceases to have any rights in the Society and ceases to incur further indebtedness to the Society.

Section 3. Any person who has ceased to be a member under Section I of this Article may be reinstated by unanimous vote of the Executive Committee subject to the payment of any outstanding dues and obligations which were incurred prior to the date when he ceased to be a member of the Society.

Section 4. Any member who, after being granted a hearing by the Executive Committee, shall be found guilty of a violation of the established principles of professional ethics, or shall be found guilty of having made a false or misleading statement in his application for membership in the Society, shall be asked to resign from the Society by unanimous vote of the Executive Committee. The decision of the Executive Committee in all matters pertaining to the interpretation and execution of the provisions of this section shall be final.

Article VII. Election of Officers

Section 1. The Standing Committee on Nominations shall consist of the President, the Past President, and the Prior Past President.

Section 2. The Standing Committee on Nominations shall nominate two or more candidates for each office to be filled. They must secure the consent of all candidates nominated.

Section 3. The Standing Committee on Nominations must submit their ticket to the President in time for publication in the October issue of the Society's journal.

Section 4. Prior to December 1, nominations in writing, signed by at least twenty Honorary Members or Active Members in good standing and accompanied by the written consent of the candidate, may be submitted to the President.

Section 5. Between December 1 and December 15, the Business Manager will prepare and mail to each member, eligible to vote, a ballot listing all candidates properly nominated for each office. With each ballot, the business manager shall send an official envelope having the member's name on the back.

Section 6. The Standing Committee on Nominations shall appoint a committee of tellers to count the ballots.

Section 7. Each member voting may cast one vote for each officer and shall return his ballot to the business manager in the official envelope carrying on the outside the written signature of the member submitting the ballot. Only ballots so prepared by members in good standing, and received by the business manager at his officially recognized address not later than January 31 shall be valid.

Section 8. The business manager shall indicate which ballots are valid, and shall deliver all ballots unopened to the tellers after February 1. The candidate receiving the greatest number of valid votes cast for an office shall be declared elected to that office. In case of a tie, the Standing Committee on Nominations shall decide by a secret vote which of the candidates shall be elected. Results of the mail ballot shall be communicated to all candidates by the nominating committee on or before February 15.

Article VIII. Local Sections

Section 1. Upon petition of twenty members in good standing residing within an appropriate distance of a central point, the Council may authorize the formation of a Local Section and assign a specific territory to the Local Section. The Council may decline to authorize the formation of a Local Section when in its judgment such an organization would not be compatible with the interests of the Society.

Section 2. In the organizing meeting of the section, all members of the Society residing in the territory assigned by the Council to the section shall be eligible to vote.

Section 3. The section shall be known as "The (name of place) Section of the Society of Exploration Geophysicists."

Section 4. The principal work of a section shall be the holding of regular meetings for the presentation and discussion of papers of interest to its members.

Section 5. The section shall adopt bylaws which must be approved by the Council of the Society and shall be consistent with the Constitution and Bylaws of the Society.

Section 6. The election of District Representatives by the Local Sections shall be by secret ballot. The term of office of a District Representative shall be two years; however, if the section is entitled to more than one representative, one of the representatives elected at the establishment of the section or added as the result of subsequent growth of the Section, shall be elected for a one year term if this is necessary to prevent the terms of all District Representatives from expiring simultaneously.

Section 7. District Representatives shall be elected at least three weeks prior to the Annual Meeting of the Society and shall take office at the close of the Annual Meeting.

Section 8. The Secretary of the Local Section shall submit to the Secretary-Treasurer of the Society a report of each meeting of the Local Section or its governing board within two weeks after the meeting. He shall submit to the Secretary-Treasurer of the Society the names of all officers and committee members within two weeks after their election or appointment.

Section 9. Any Local Section which for two consecutive years has among its membership fewer than twenty members in good standing of the Society shall automatically be dissolved by the Council at its annual joint meeting. The Council may at any time dissolve any Local Section for reasons it deems good and sufficient.

Article IX. Finances of Local Sections

Section 1. The Society may, at the discretion of the Council, pay any portion of the necessary operating expenses of a Local Section up to the sum of the following amounts: (a) $100 per year; (b) $50 per meeting up to four meetings per year; (c) $0.50 per member of the Society.

Section 2. The Treasurer of the Local Section shall forward, from time to time, his application for such portions of the sum provided in Section 1 as may be needed to the Secretary-Treasurer of the Society, who will arrange for the issuance of a check for the requested amount to the Treasurer of the Local Section.

Section 3. Prior to the Annual Meeting, the Treasurer of each Local Section shall transmit to the Secretary-Treasurer of the Society, for approval by the Council, an itemized statement of the expenditure of the funds received from the Society during the preceding calendar year.

Section 4. Allocations to a Local Section for the year in which it is established shall be in proportion to the fraction of the calendar year remaining.

Section 5. The Local Section may levy dues or raise funds in any other manner, subject to the approval of the Council. Payment of local dues shall, however, not be a prerequisite to participation in any activity financed wholly or in part with funds received from the Society.

Article X. Standing Committees

Section 1. The Society shall have the following standing committees: (a) Standing Committee on Nominations; (b) Standing Committee on Membership; (c) Standing Committee on Honors and Awards; (d) Standing Committee on Publications; (e) Standing Committee on Program and Ar-

rangements; (f) Standing Committee on Education; (g) Standing Committee on Student Membership; (h) Standing Committee on Distinguished Lectures; (i) Standing Committee on Radio Facilities; (j) Standing Committee on Reviews; (k) Standing Committee on Public Relations; (l) Standing Committee on Publicity; (m) Standing Committee on Geophysical Activity; and (n) Standing Committee on Safety.

SECTION 2. Each standing committee shall have a chairman, appointed by the President unless otherwise specified in these Bylaws. The chairman shall submit a report to the President of the Society at such intervals as the chairman may deem advisable but at least quarterly. He shall submit to the Council at its annual joint meeting a report covering the activities of the committee since the previous Annual Meeting.

SECTION 3. The Standing Committee on Nominations shall consist of the President who shall be chairman, the Past President, and Prior Past President. Its duties shall be to nominate candidates for officers, appoint tellers to count the ballots and to declare the election of the officers as prescribed in Article VII of these Bylaws.

SECTION 4. The Standing Committee on Membership shall consist of three Active or Honorary Members appointed for a period of one year by the President immediately following the Annual Meeting. One of the members appointed shall have been a member the preceding year. The Committee shall actively solicit applications for membership from those qualified. It shall work closely with the membership committees of the Local Sections.

SECTION 5. The Standing Committee on Honors and Awards shall consist of five Active or Honorary Members, none of whom shall have been members of the Society less than five years. The senior member of the committee shall retire after the Annual Meeting. Vacancies shall be filled by the President. The Committee shall recommend candidates for election to Honorary Membership to the Council. The Committee shall recommend to the Council the establishment of honors and awards and shall recommend candidates for all established honors and awards of the Society to the Council.

SECTION 6. The Standing Committee on Publications shall consist of five Active or Honorary Members who shall serve a two year term concurrent with the Editor and who shall be appointed by the Editor. The committee shall have the duty of advising and assisting the Editor. The Editor shall appoint the chairman of this committee.

SECTION 7. The Standing Committee on Program and Arrangements shall consist of the District Representatives plus three to ten additional members of any class appointed for a term of one year by the Vice-President, who shall be chairman. The names of the members of the committee shall be published in the July issue of the Society's journal. The committee shall have the duty of assisting the Vice-President in arranging and holding the Annual Meeting.

SECTION 8. The Standing Committee on Education shall consist of five persons appointed for one year by the President. The chairman shall be an Active or Honorary Member. The committee shall promote effective geophysical education.

SECTION 9. The Standing Committee on Student Membership shall consist of five persons appointed for one year by the President. The chairman shall be an Active or Honorary Member. The committee shall encourage the interest of students in geophysics and the Society.

SECTION 10. The Standing Committee on Distinguished Lectures shall consist of six persons appointed for three years by the President. The two senior members of the committee shall retire after the Annual Meeting. The chairman of the committee shall be appointed for one year by the President, and shall be an Active or Honorary Member. The committee shall obtain distinguished lecturers in geophysics and plan and supervise tours by these lecturers to the Local Sections of the Society and other participating organizations.

SECTION 11. The Standing Committee on Radio Facilities shall consist of from 5 to 15 Active or Honorary Members appointed for one year by the President. The committee shall, upon request from its chairman, determine the opinions of the members of the geophysical industry concerning matters pertaining to the use of radio in geophysics.

SECTION 12. The Standing Committee on Reviews shall consist of from 5 to 10 members who

need not be Active Members of the Society. The members and the chairman shall serve a two year term concurrent with the Editor and shall be appointed by the Editor. The committee shall prepare reviews of current geophysical literature for publication in *Geophysics*.

SECTION 13. The Standing Committee on Public Relations shall consist of a chairman, appointed for one year by the President, and such additional members, appointed for one year by the chairman, as he may deem desirable. The committee shall advise the officers and Council of the Society concerning matters pertaining to public relations, shall recommend public relations policy, and shall carry out projects to promote good public relations.

SECTION 14. The Standing Committee on Publicity shall consist of a chairman, appointed for one year by the President, and such additional members, appointed for one year by the chairman, as he may deem desirable. The committee shall prepare and arrange for the distribution of suitable publicity material for the press, radio, and other appropriate media.

SECTION 15. The Standing Committee on Geophysical Activity shall consist of four or more Active or Honorary Members of the Society appointed for a term of one year by the President. The committee shall conduct an annual survey of geophysical activities throughout the world. This report shall be presented before the Society at its Annual Meeting and published in the July issue of *Geophysics*. It may be made available for publication in leading trade journals for release at the time of the annual meeting.

SECTION 16. The Standing Committee on Safety shall consist of a chairman, appointed for one year by the President, and such additional members, appointed for one year by the chairman, as he may deem desirable. The committee shall recommend safety policy and shall carry out projects to promote safety in geophysical operations.

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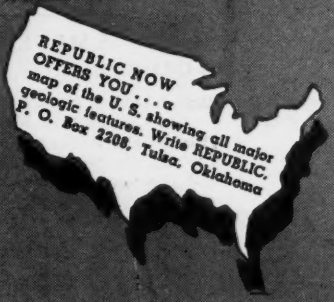

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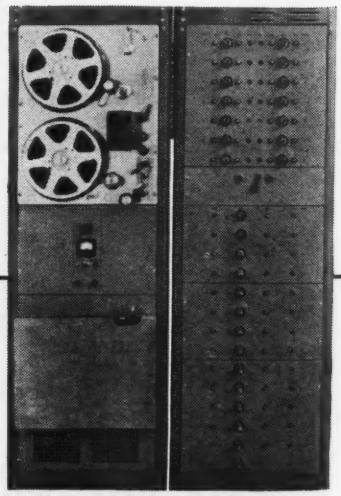

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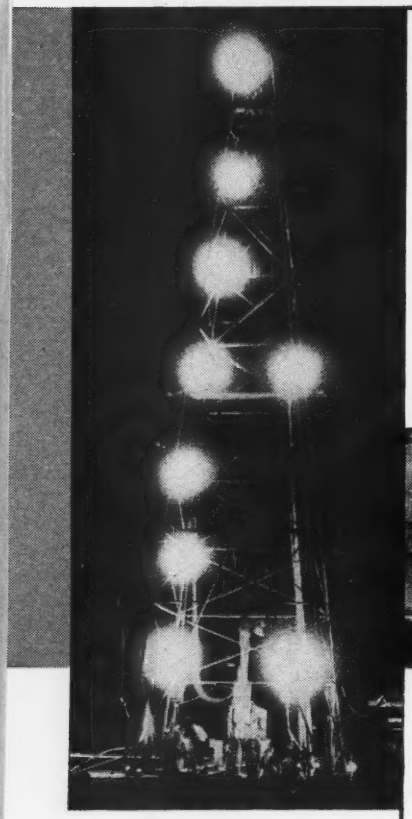

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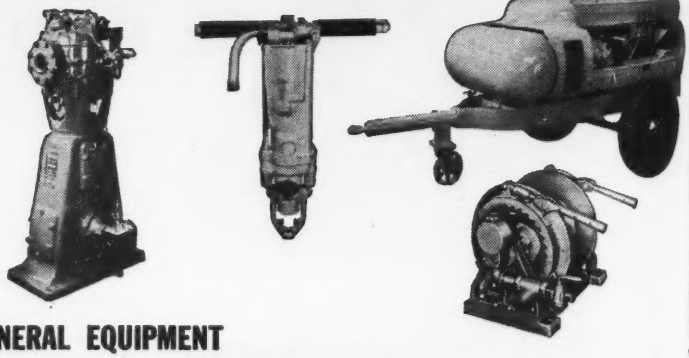

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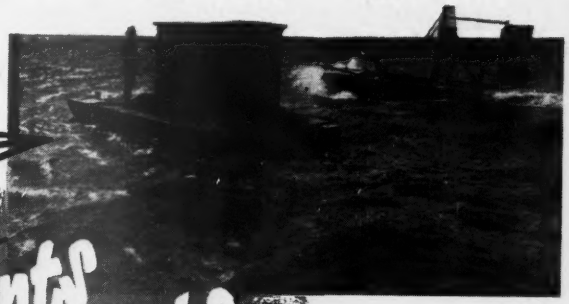

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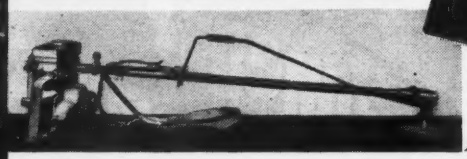

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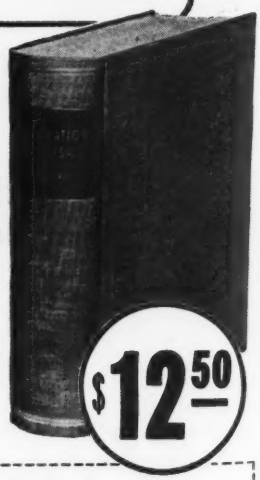

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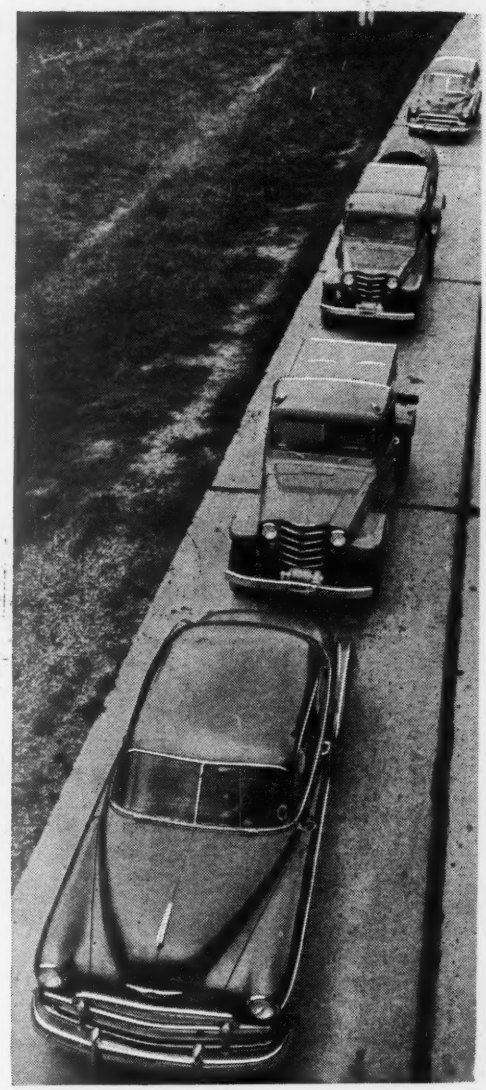

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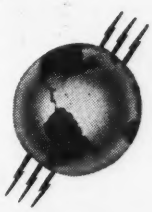

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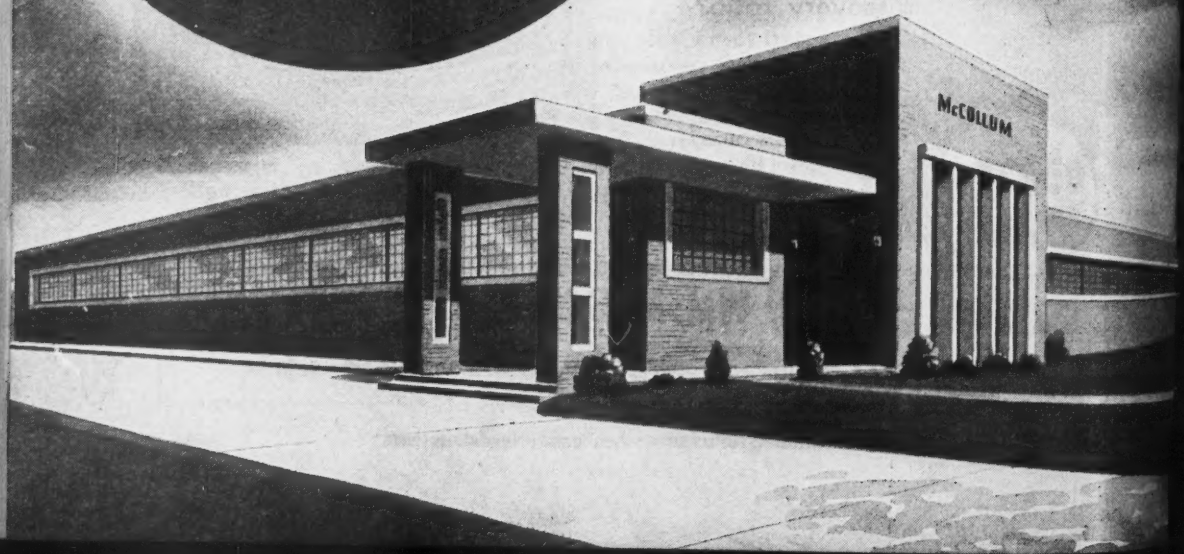

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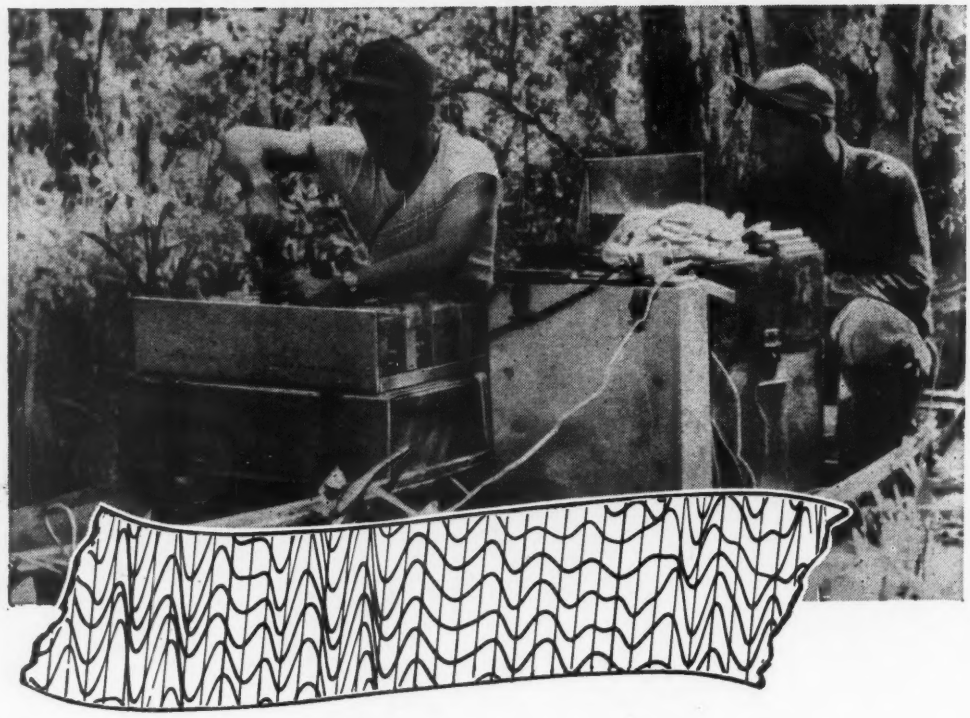

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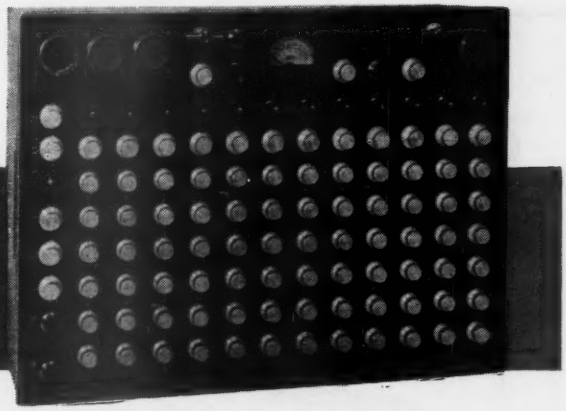

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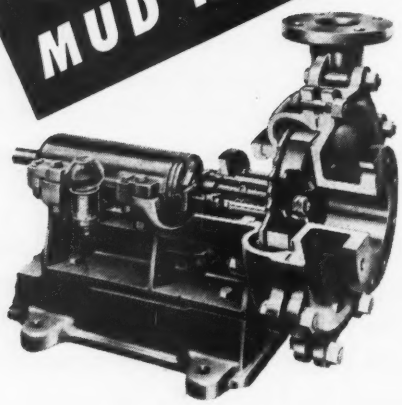

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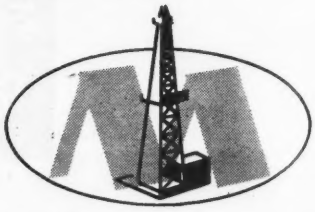

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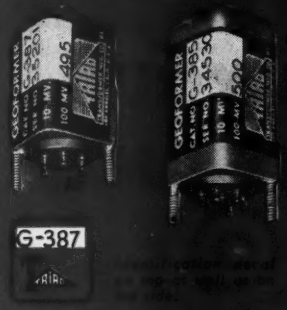

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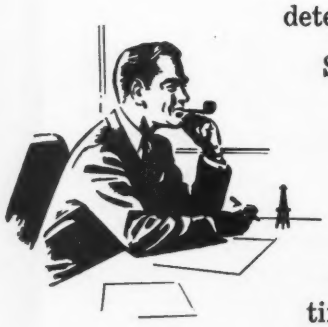

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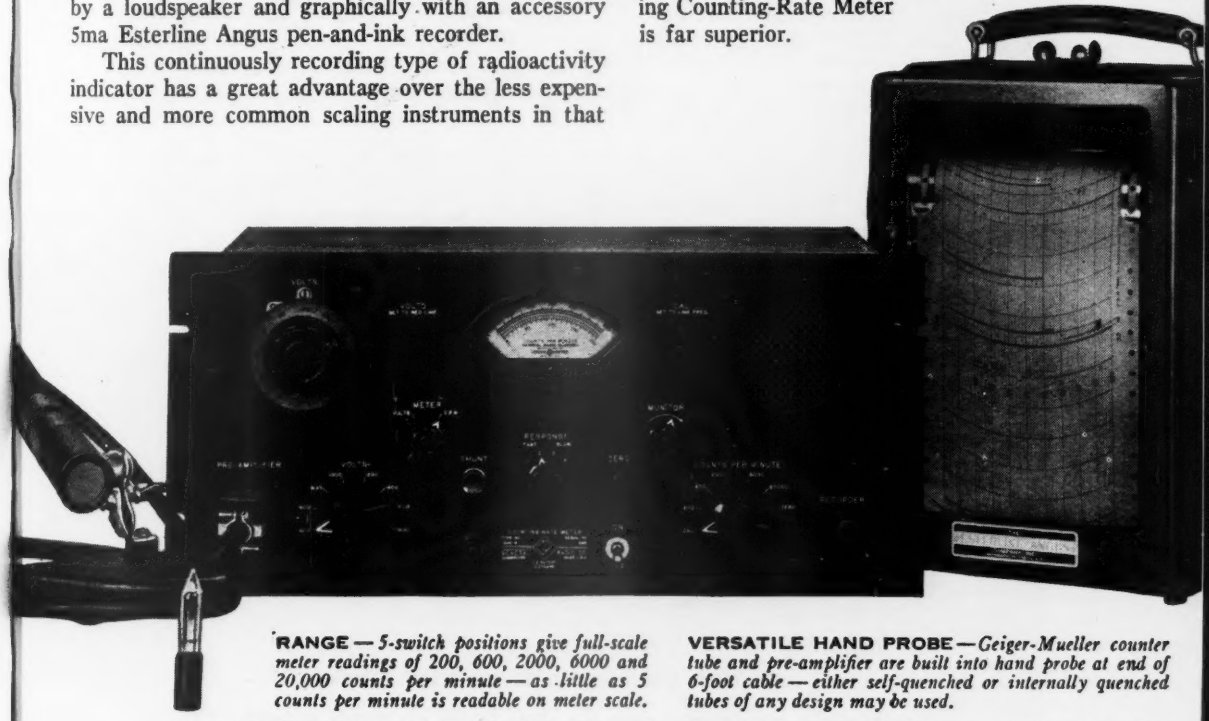

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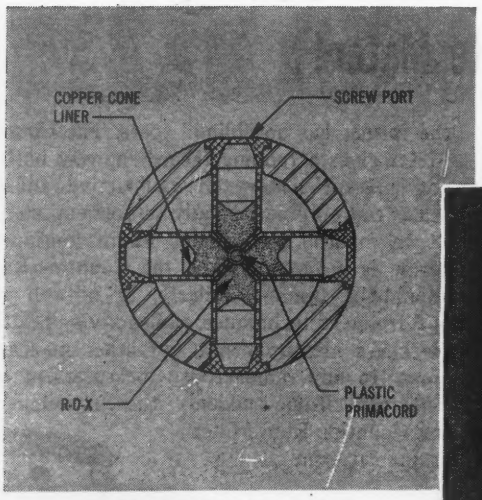

The diagram above shows the charge arrangement in the "4-Way" gun.

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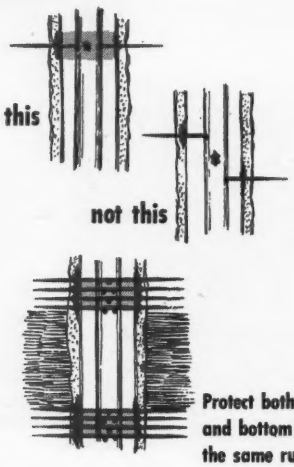

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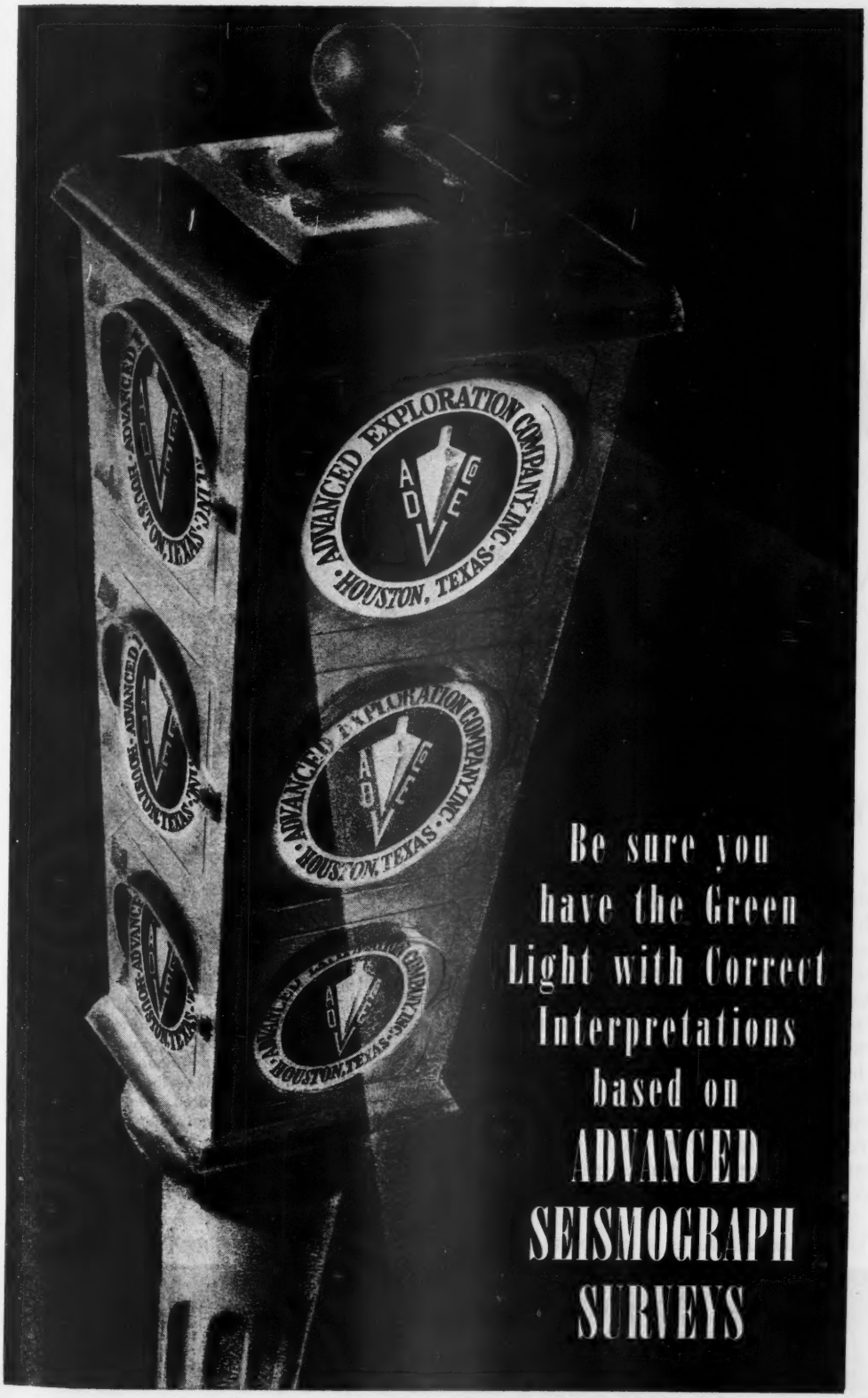
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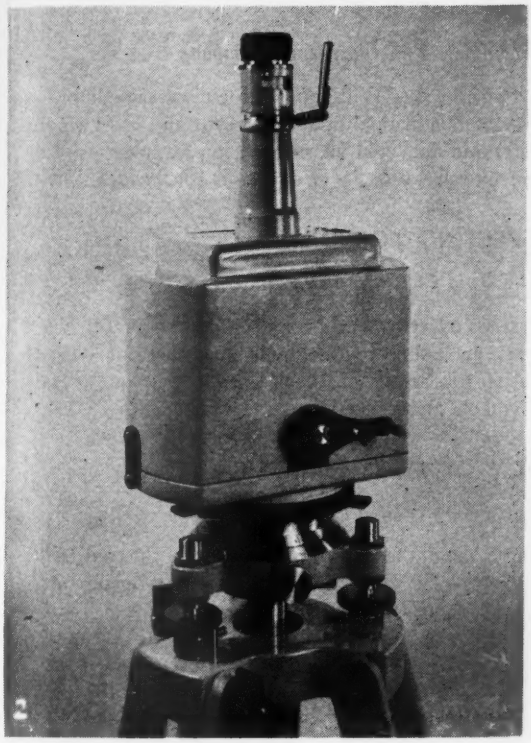

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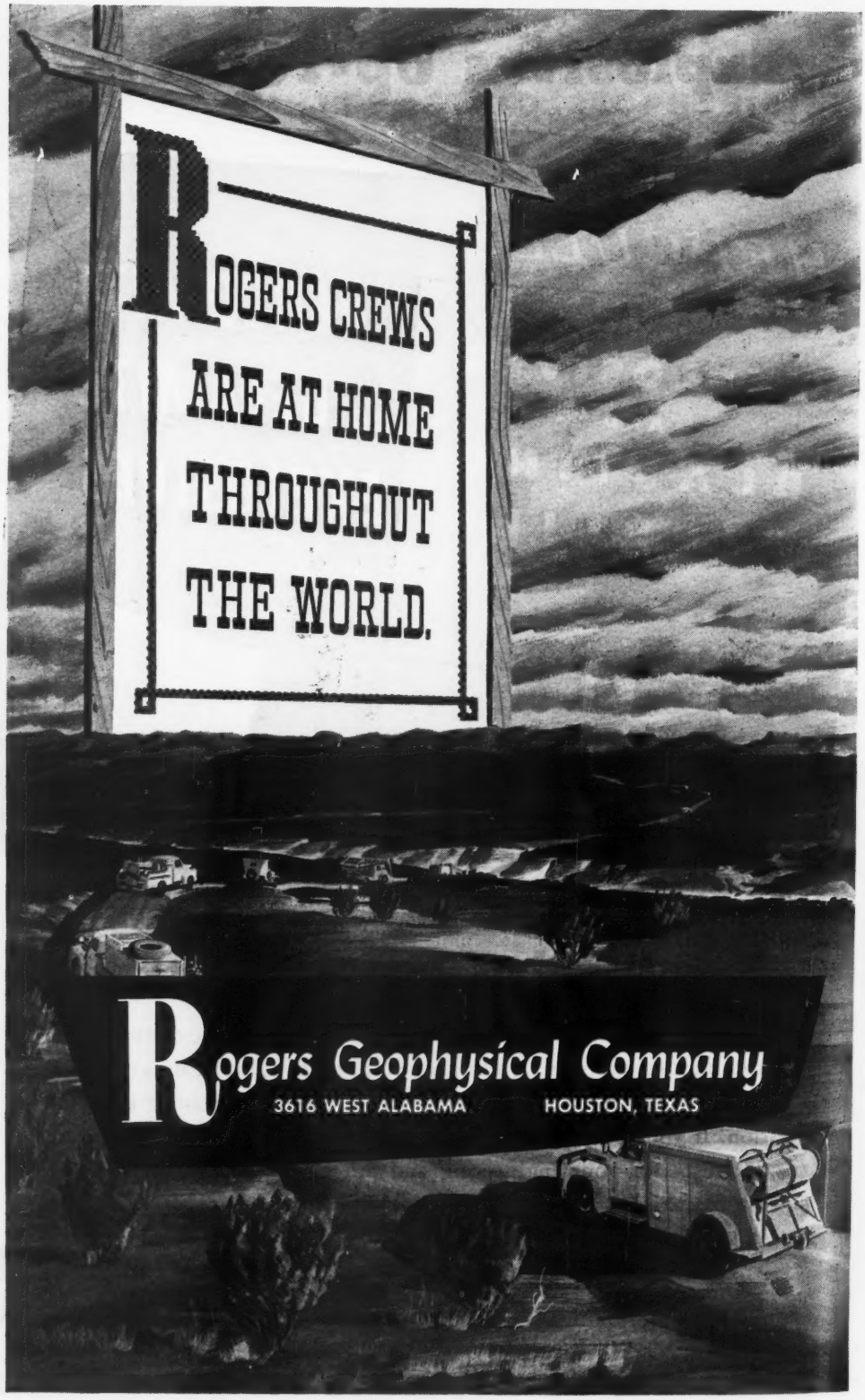
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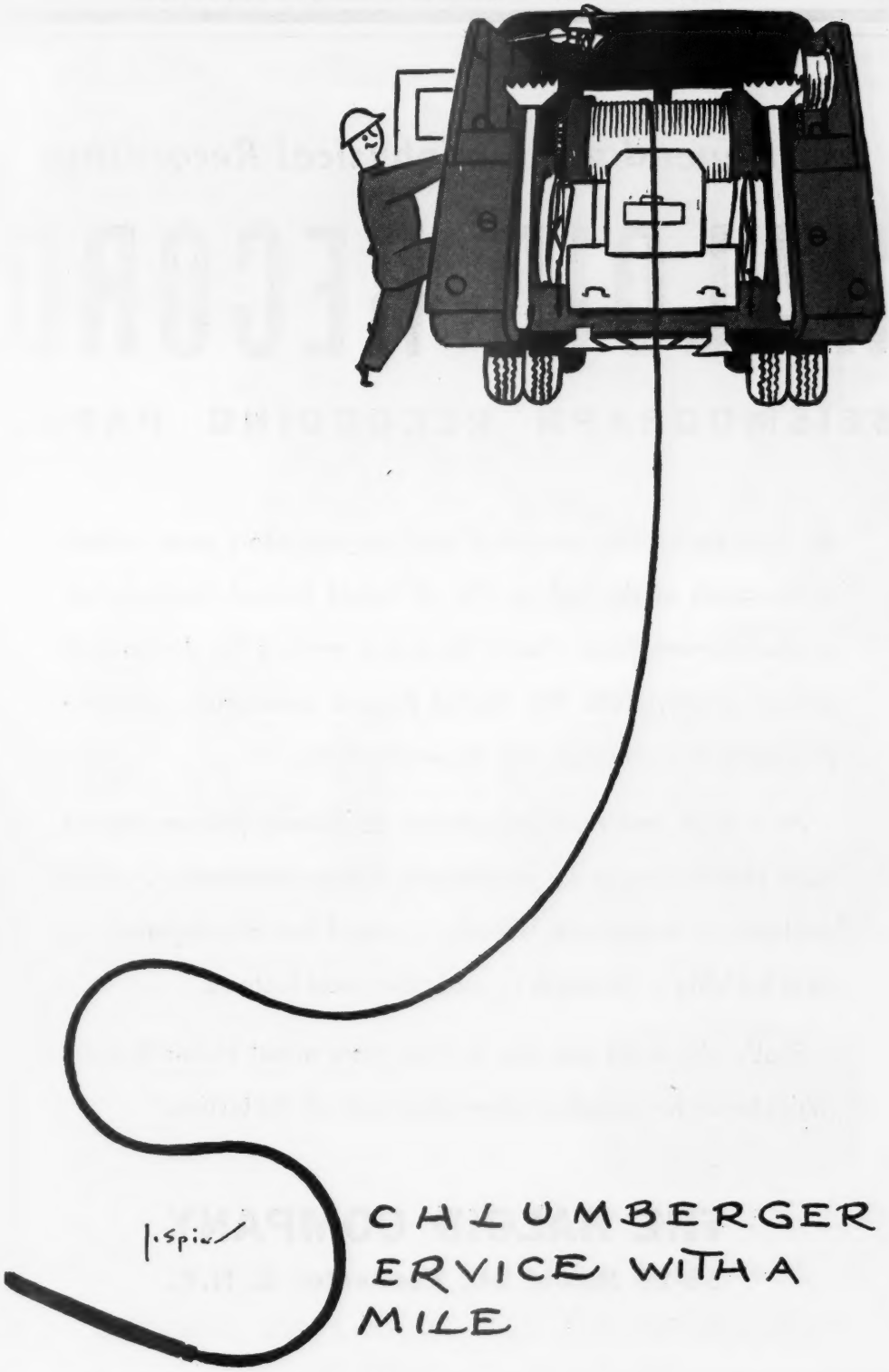

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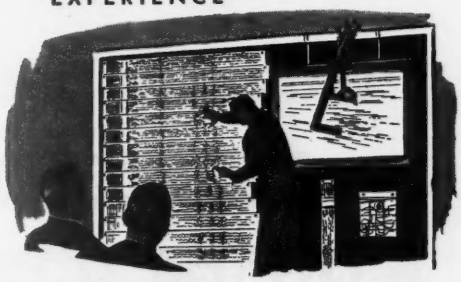

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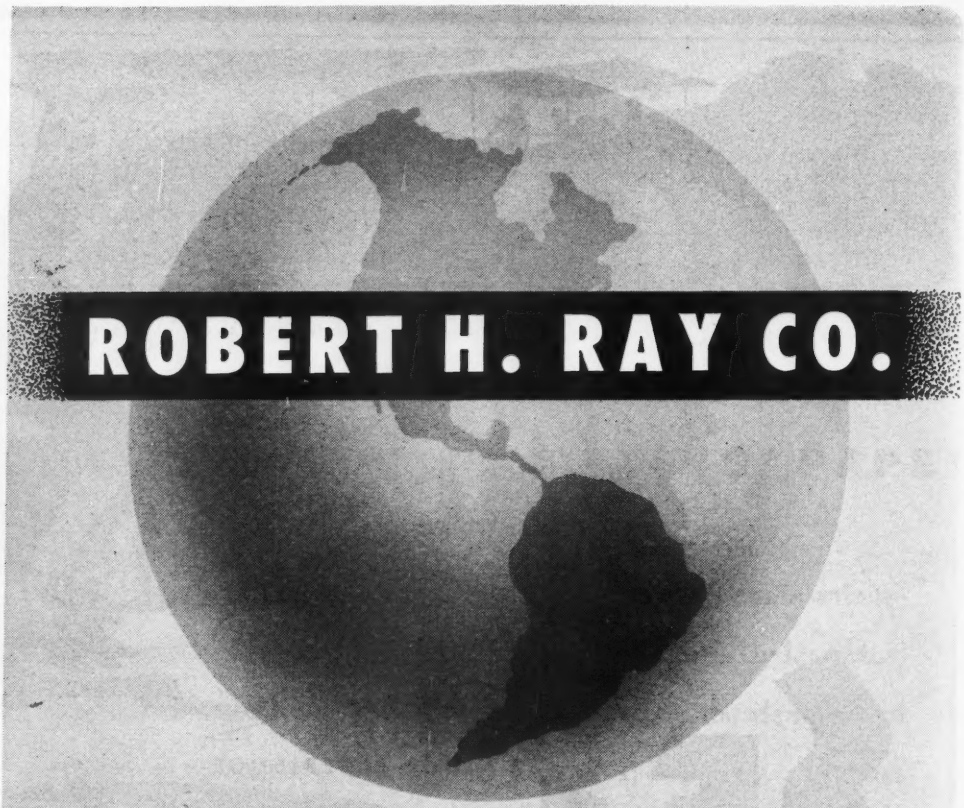

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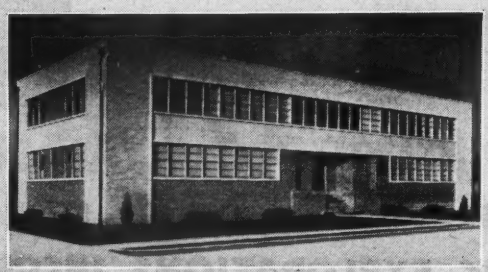

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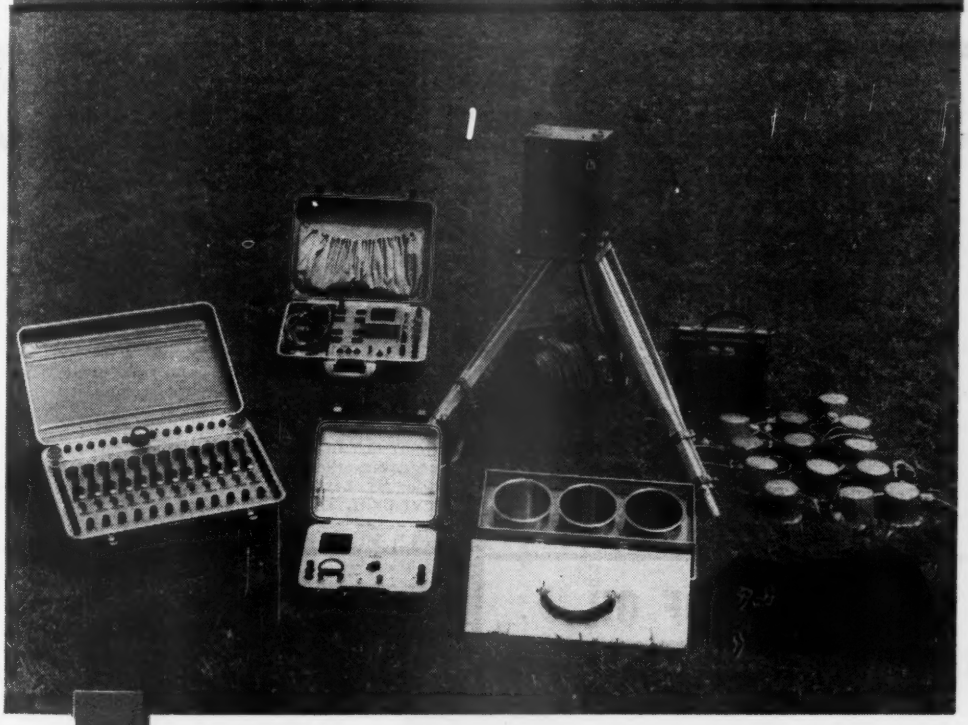

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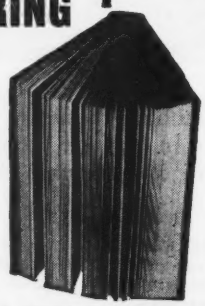

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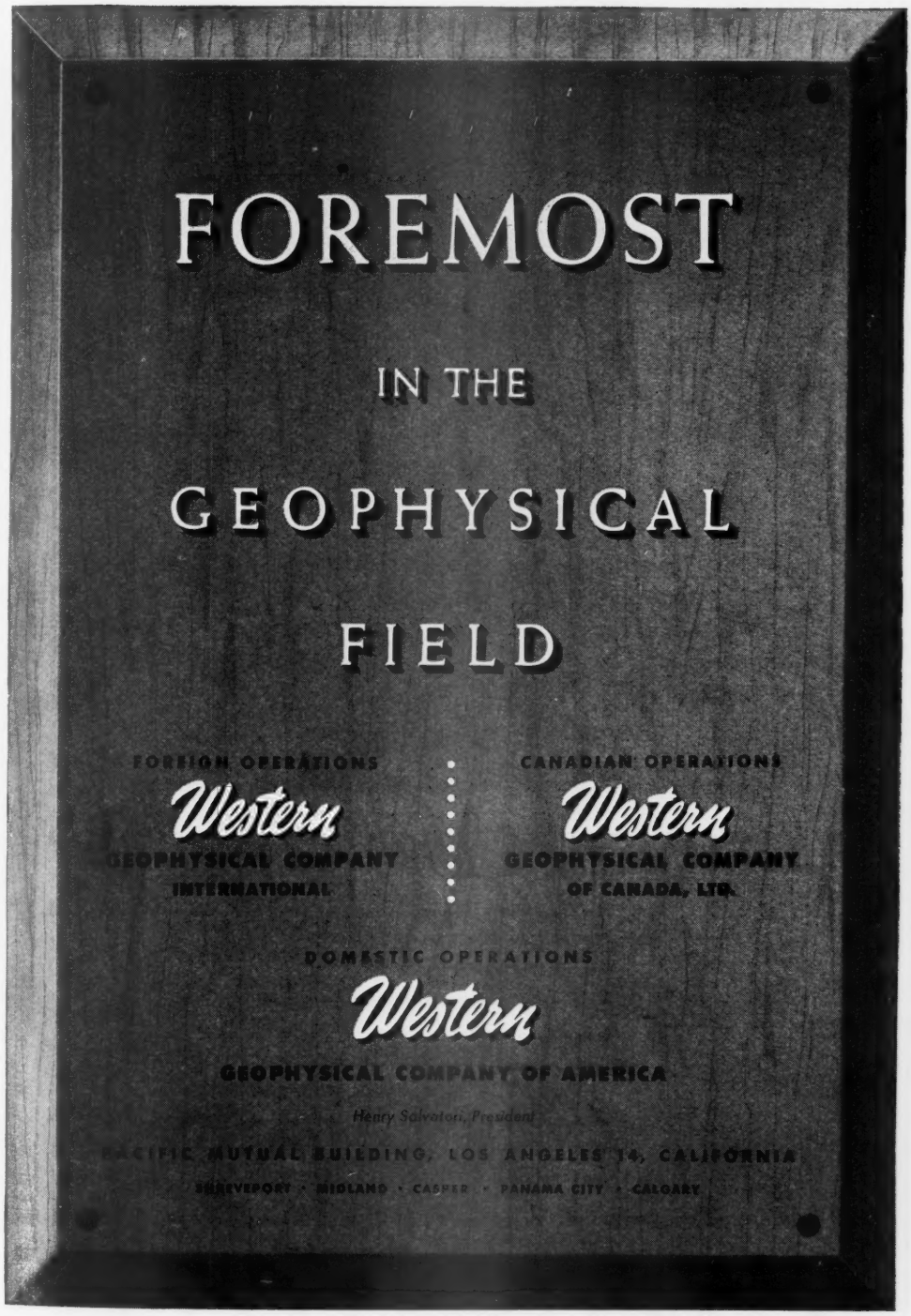
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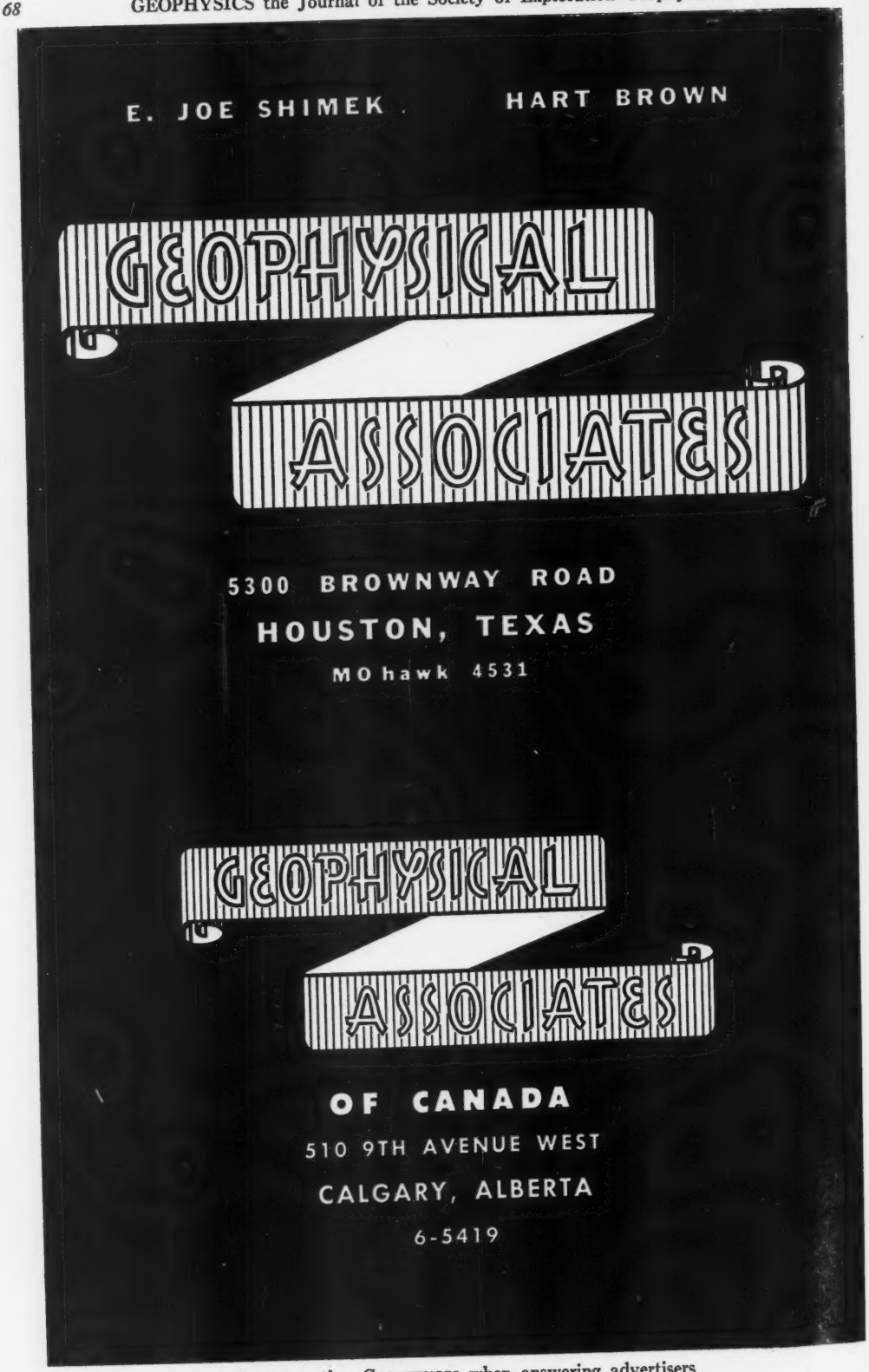
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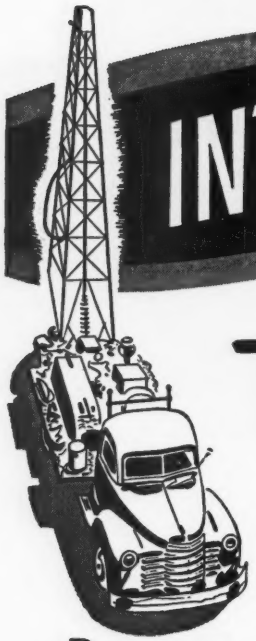

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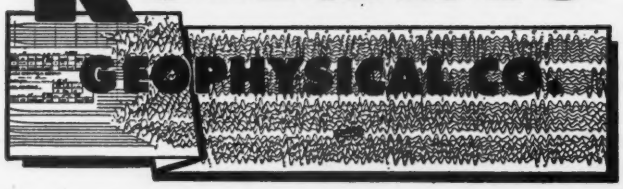

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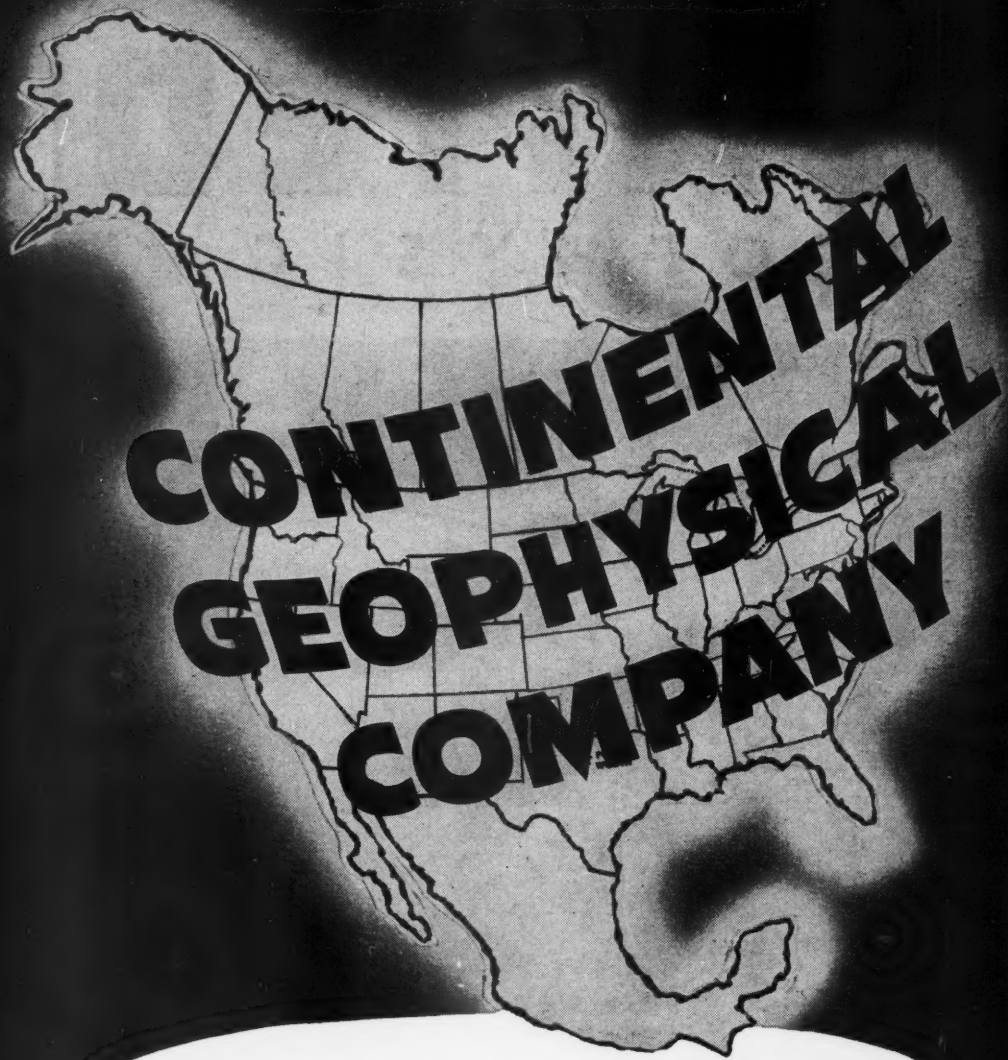

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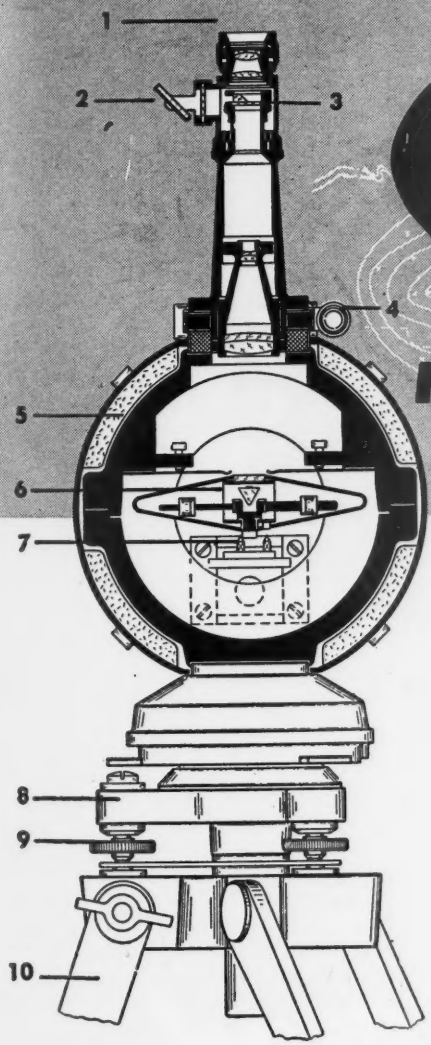

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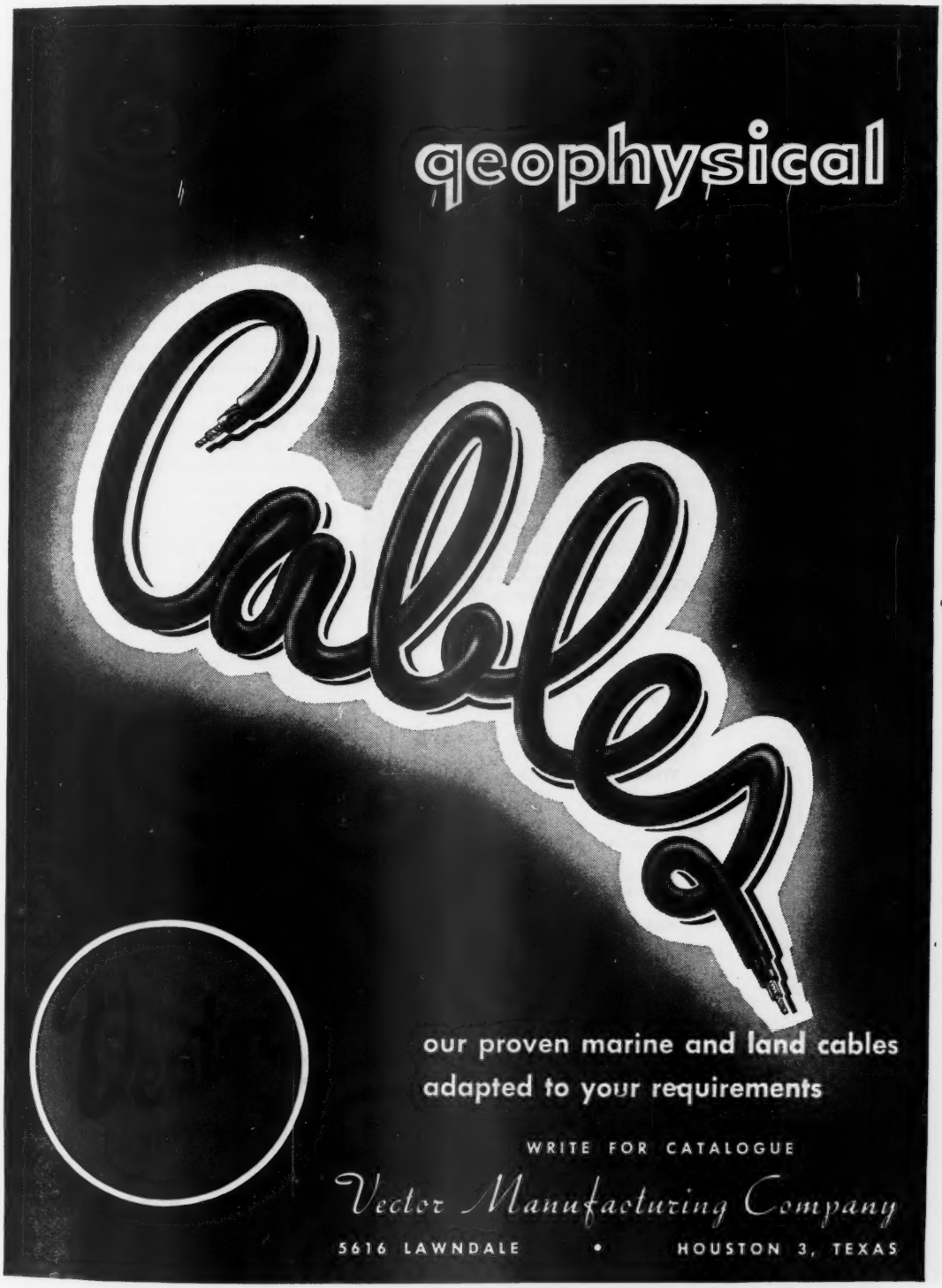
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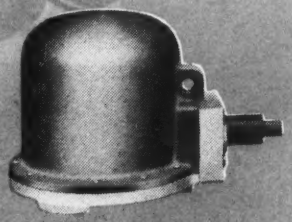

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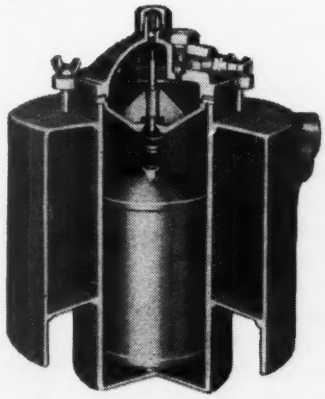

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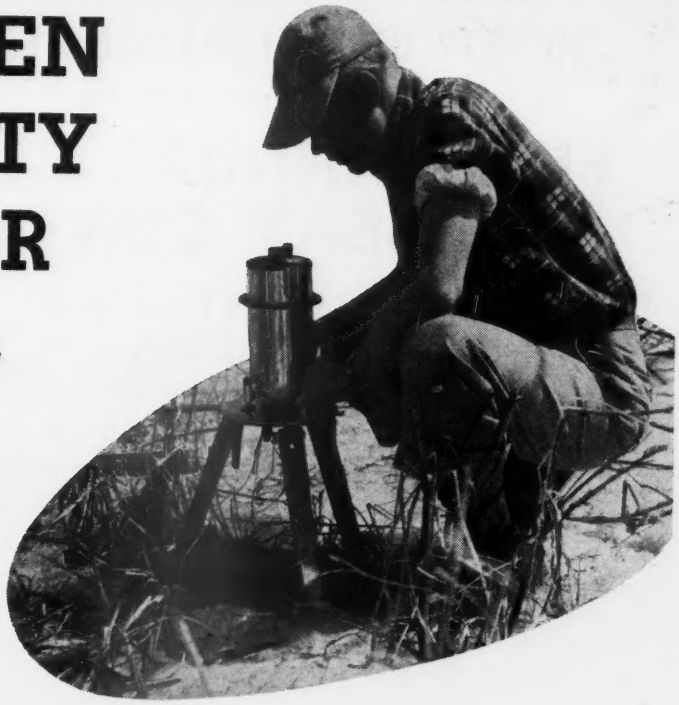

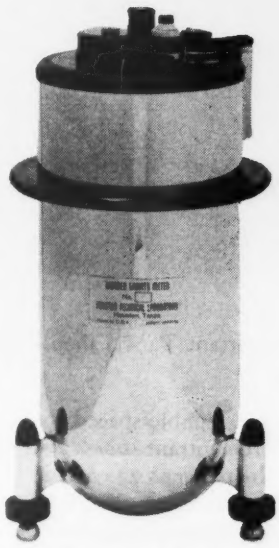

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RULES

SUBJECT MATTER: Subjects to be chosen from the field of exploration geophysics or physics of the earth. Must be an *original* work and a new contribution to the literature of geophysics. No restriction as to treatment—may be scientific exposition or discussion of economic or philosophic aspects of subject.

(Suggested subjects: a new instrument, technique, method or theory in geophysics, or a previously undescribed geophysical case history.)

ELIGIBILITY: All undergraduate students enrolled for at least one course in geophysics are eligible to enter. *Membership in a student chapter of SEG or affiliated groups is not a prerequisite.*

LENGTH OF ESSAY: Brevity and conciseness in writing are important. Papers should not exceed maximum limit of 5000 words, including abstract.

PREPARATION OF MANUSCRIPT: Manuscripts should be typed, double-spaced, on $8\frac{1}{2} \times 11$ white paper, and submitted in quadruplicate. Name of the entrant *should not* appear on the manuscript, but a letter of transmittal identifying the paper as an entry in the First Student Essay Contest of the SEG should accompany each manuscript. Conventional rules of composition apply for footnotes and citations. Illustrations may be inserted in the text or included in an appendix. *Neatness, accuracy of punctuation, and grammatical quality will be considered in the decision of the judges.*

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PUBLICATION: Winning essay may be published in *Geophysics,* the Journal of the Society of Exploration Geophysicists, at the discretion of the Editor. Contest entrants retain all publication rights to their essays.

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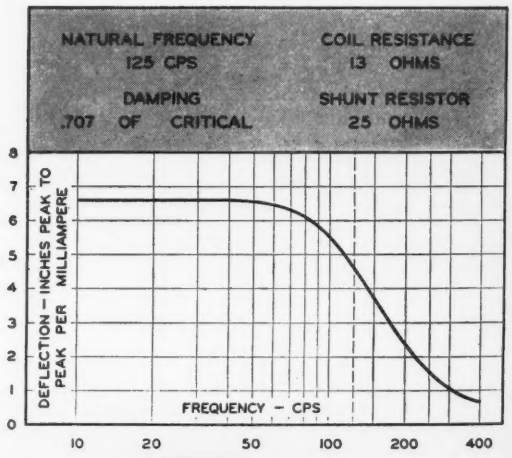

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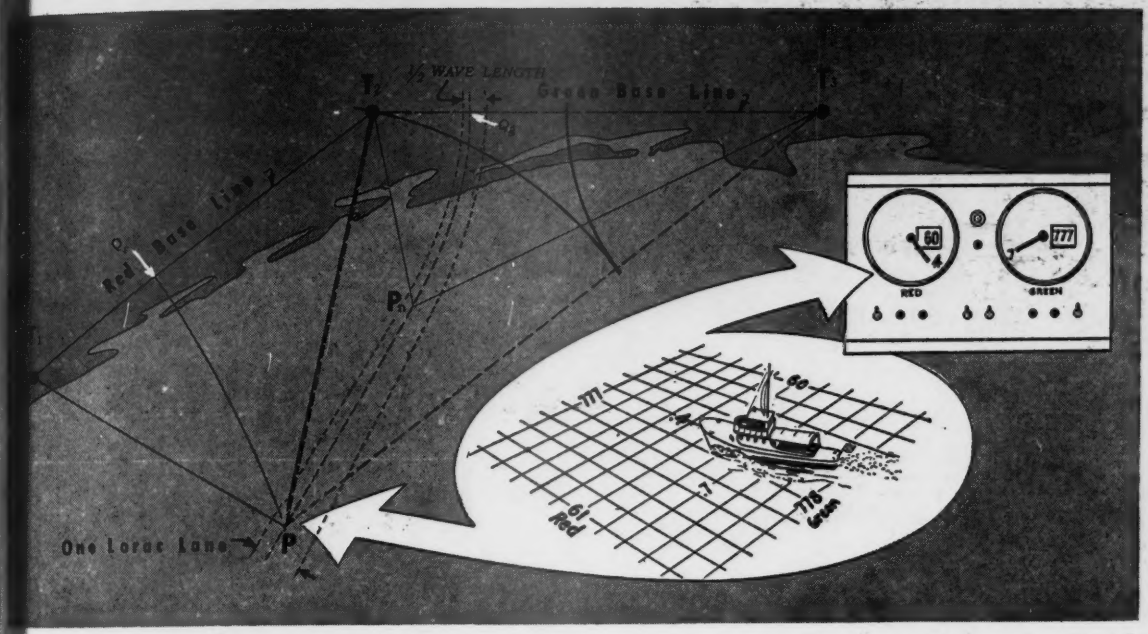

LORAC---
its purpose and principle

The purpose of Lorac is to provide an accurate and convenient means of establishing position. A position not dependent on visibility, or on the use of short-range, *high-frequency* radio waves.

The basic principle of Lorac is the determination of the position at a point P with respect to three low frequency radio transmitters.

This is accomplished by phase-meters which indicate indirectly the *difference in distance* between the point P and two fixed land-base transmitters such as T_1 and T_2, or T_2 and T_3.

With only two transmitters there are a series of points whose *difference in distance* to the transmitters is the same. This series of points (P, P_n, etc.) lie on a hyperbolic curve.

Therefore to obtain a fix at point P, three transmitters are required providing two hyperbolas whose intersection locates the exact point in question.

The Lorac phase-meters indicate position to 1/100 part of the spacing between two hyperbolic lines called "lanes" which are separated on the base-line by a distance equal to ½ the wave length of the transmitted continuous-wave signals.

Thus an accuracy of *plus or minus 2.5* feet is possible on the base-line between the transmitters of the Gulf Coast Lorac networks.*

This accuracy decreases somewhat out to sea due to the lane expansion. However, for distances up to 100 miles off-shore, the positioning accuracy of Lorac is more than sufficient for all types of geophysical operations.

* Three networks in operation covering an area from off the Coast of Freeport, Texas, to Caillou Bay, Louisiana.

LORAC

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